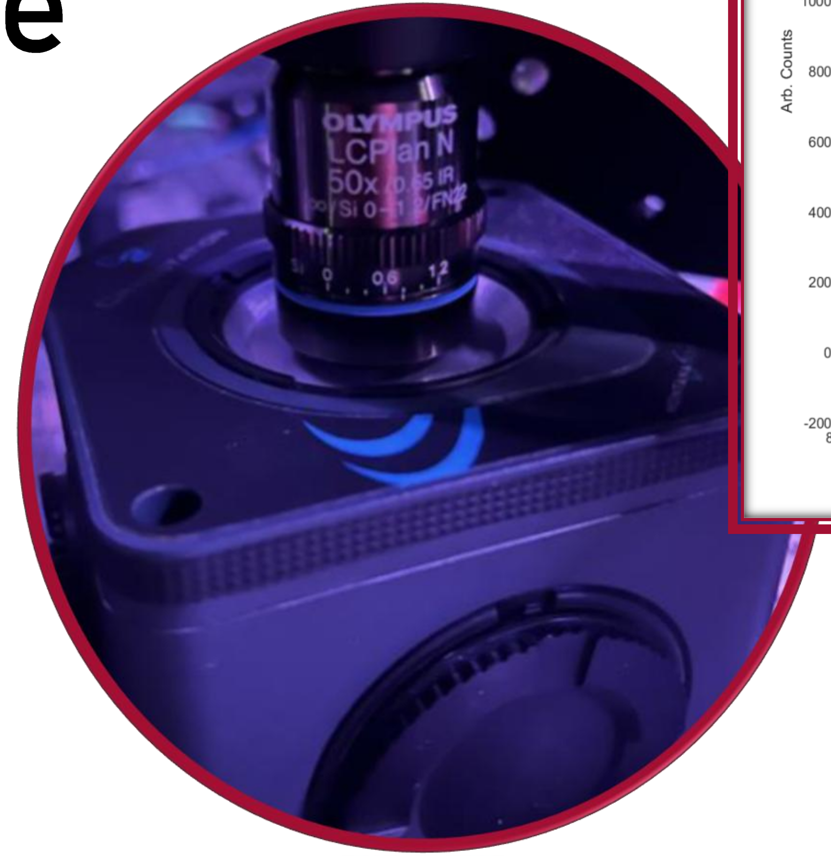
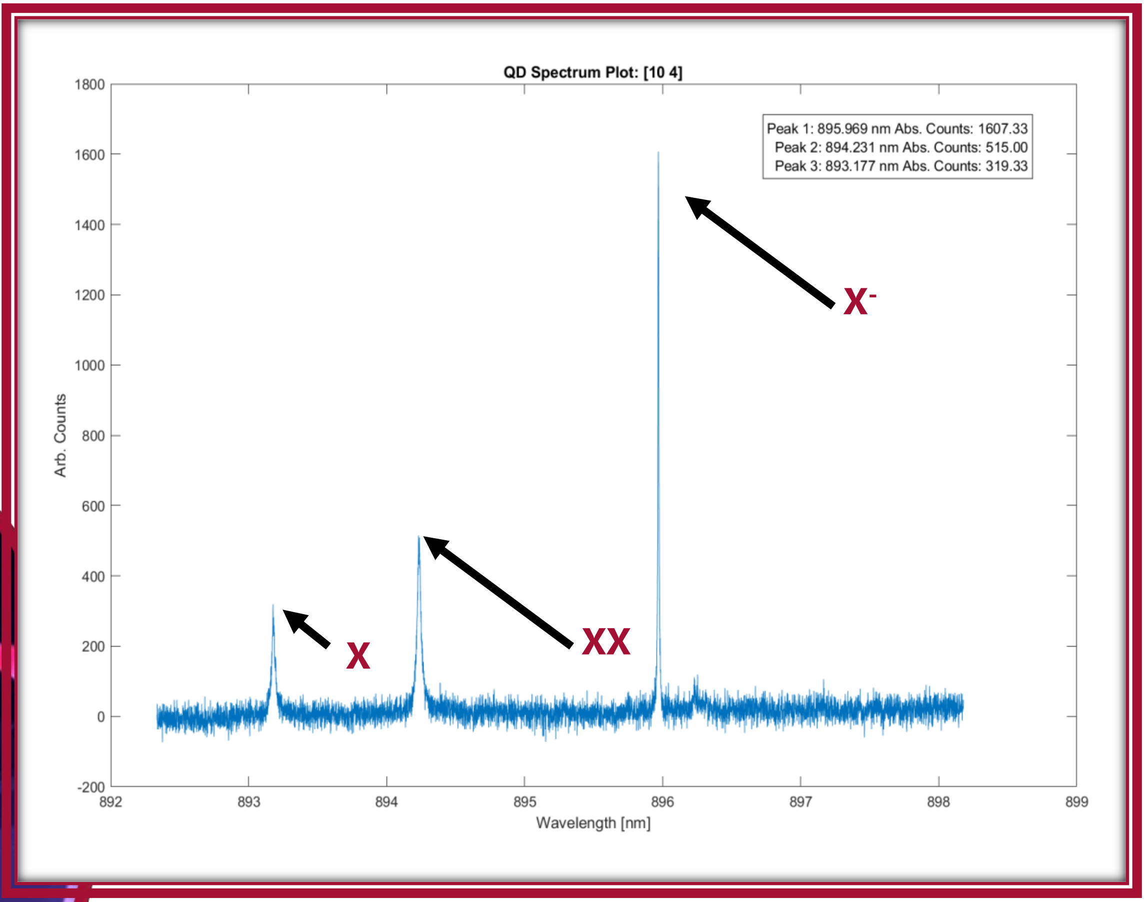
Finding the Perfect Quantum Dot (QD)

Bera Emin Yavuz
Undergrad Research Co-op

Cryostat Nanowires Sits in



Angles 0 -180 Degrees (QD [10 4]



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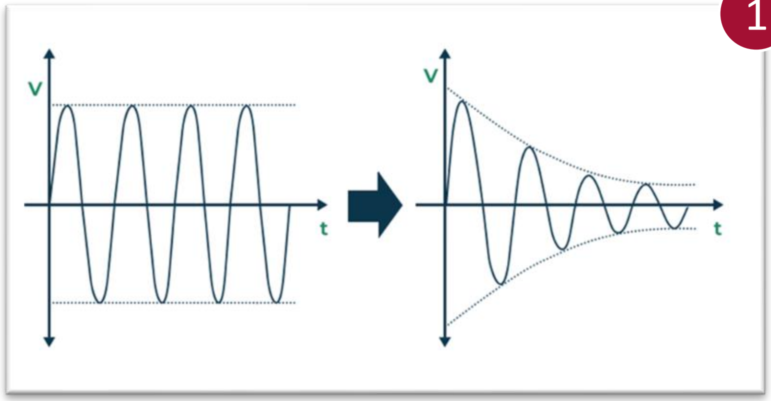
Big Picture

Quantum Repeater (End Goal)

- Crucial component in long-distance quantum communication
- Extends the range of quantum communication by overcoming limitations;
  - **- Signal attenuation**
  - **- Decoherence**
  - **- No-Cloning Theorem**
- Need the perfect entangled photon source **A.K.A find the perfect QD**

1



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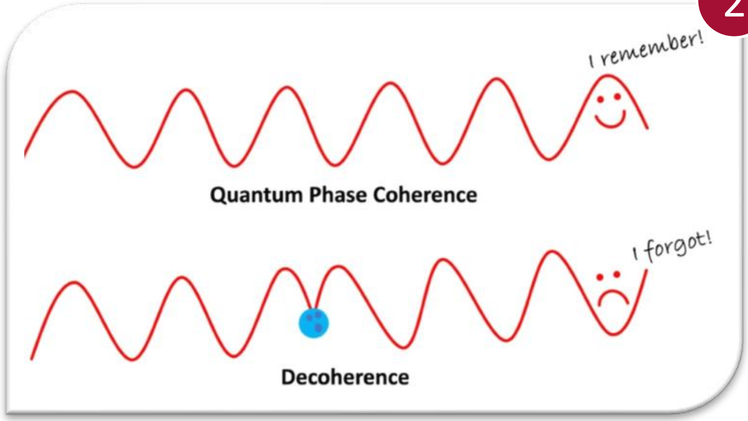

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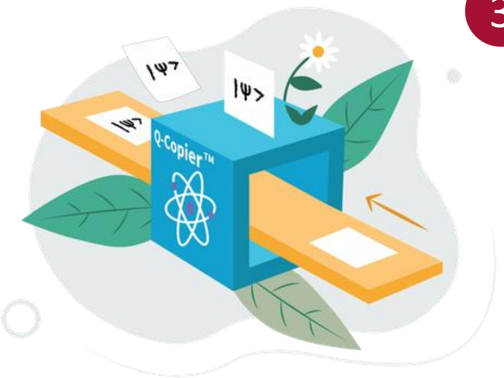
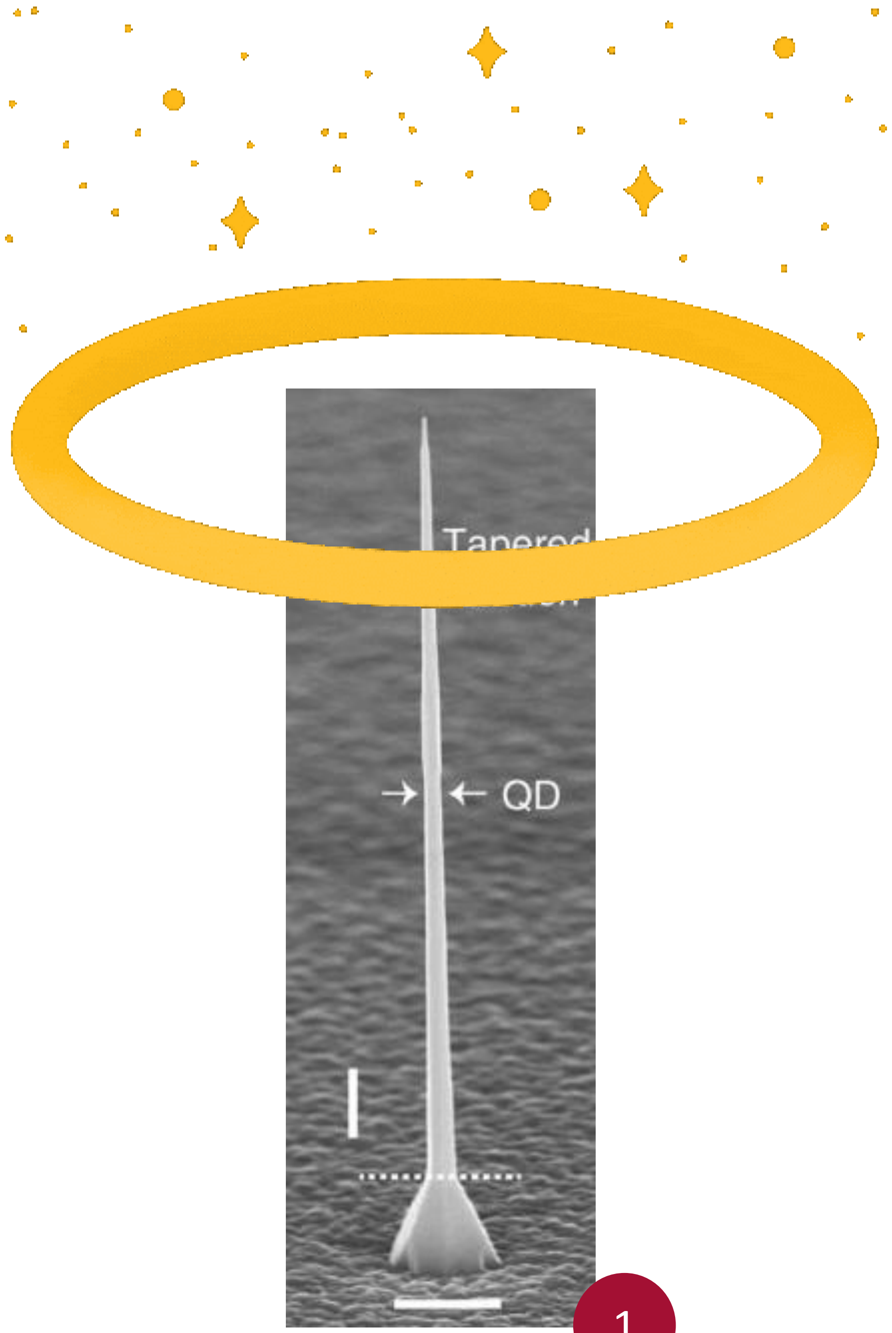


1. Google Images
2. Google Images
3. Google Images

What is the Perfect QD?

1. QD must “talk” with **Cs atom**
2. Must be **Considerably Bright**
3. Produce Good **Quality Entangled Photons**

But what are these things exactly?

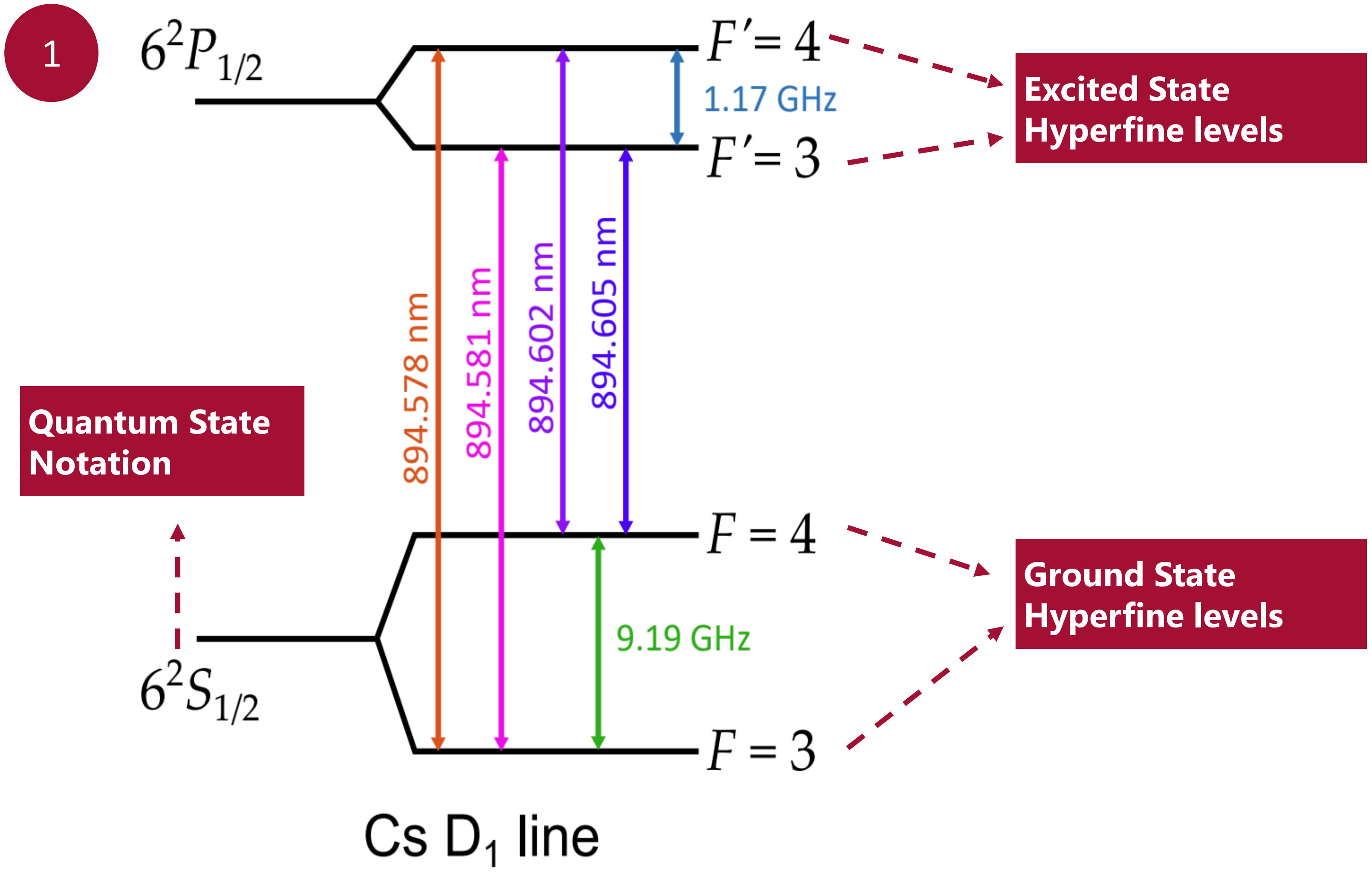


[1]

1. Reimer, Michael E., et al. "Bright Single-Photon Sources in Bottom-Up Tailored Nanowires." *Nature Communications*, vol. 3, 2012, p. 737

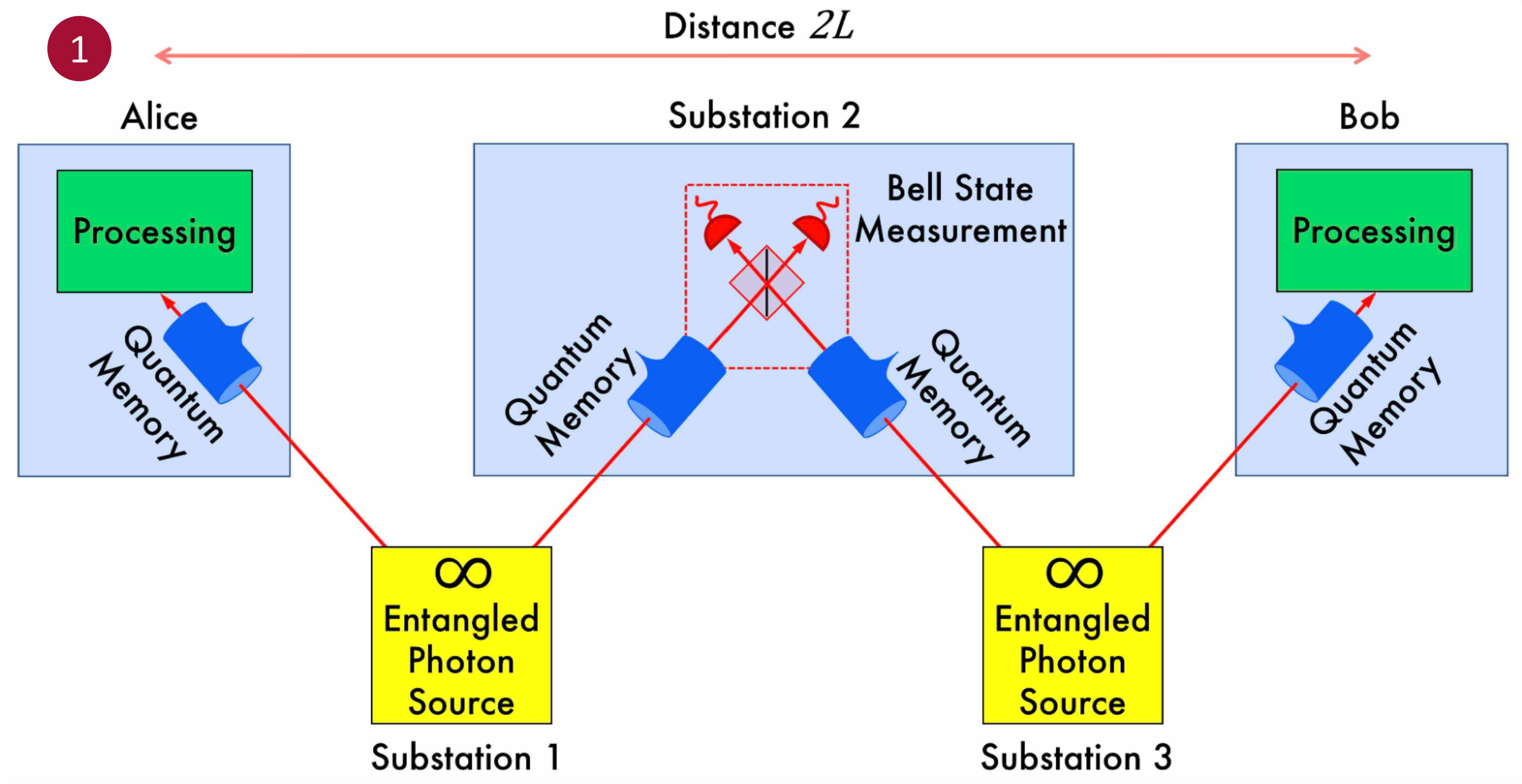
“Talking” with Cesium Atoms

- Photons wavelengths emitted by QD must match the **D1 Transition Line of Cesium** [1]
- **4** Possible **“perfect wavelengths”**
- Matching **transition lines ensures coherent interaction**, improving the **fidelity** of stored quantum states.



Cesium Atom Energy levels (D1 transition line)

1. Rubayet’s Manuscript

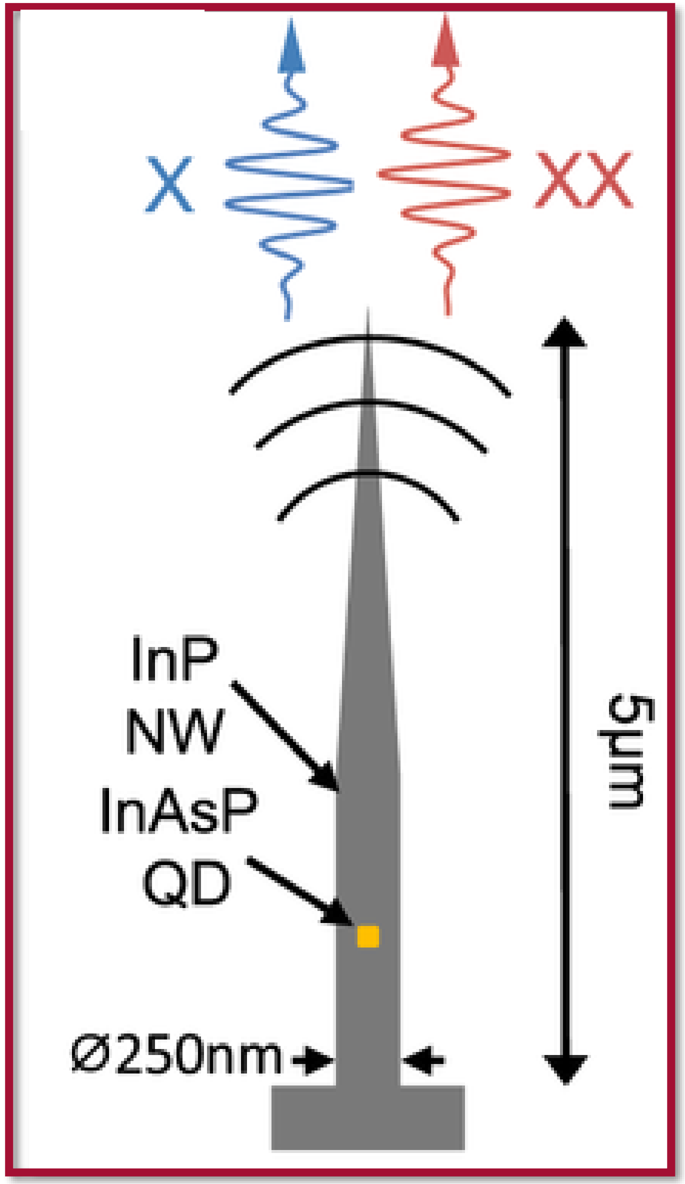


Quantum Memory:
- Caesium (Cs)

Entangled Photon Source:
- Photons emitted from QD

1. Figuero Research Group

How do we excite a QD?



QD Excitation Simple Overview

Quantum dots = semiconductor nanocrystals

Electrons are **confined** → discrete energy levels

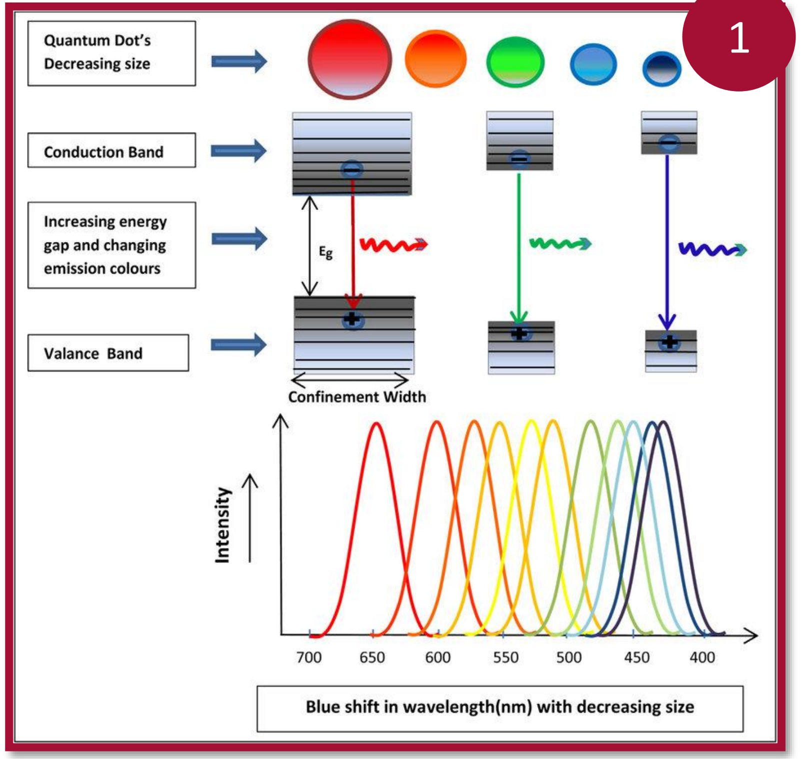
Laser excites an electron → moves to **higher energy level**

Forms **exciton** (electron + hole pair)

Electron falls back → emits a **photon** (light)

Quantum Confinement Effect

1

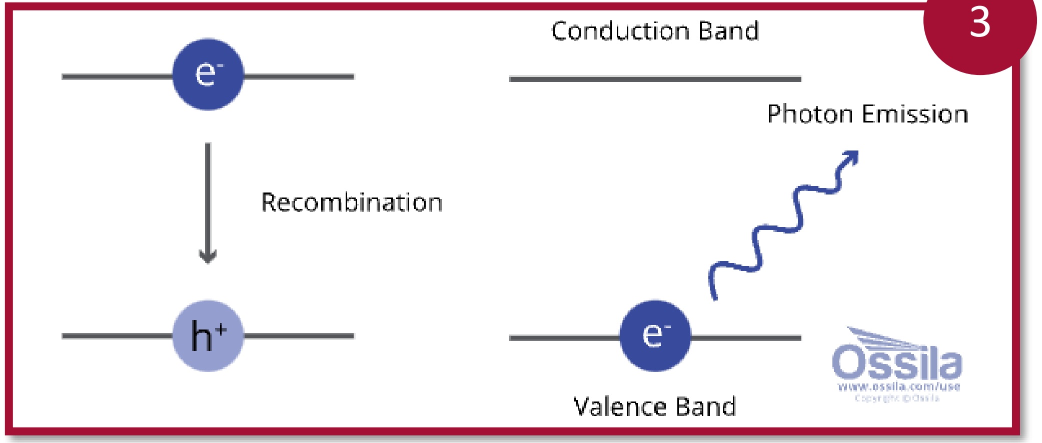


Exciton Formation

2

Photon Emission

3



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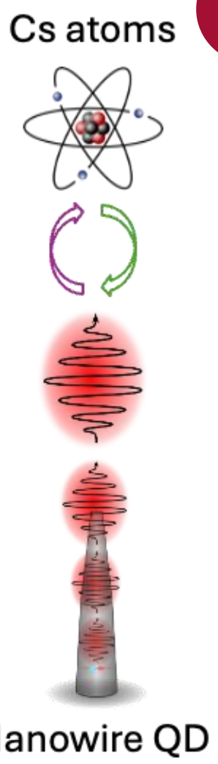


QD Emitting Photon

1. Google Images
2. Google Images
3. Google Images
4. Fine Structure Splitting of Quantum Dots By Katie McDonnel

Different Methods of Excitation

a) Above-Band

Laser Requirements:
- Any laser **above the bandgap** of the barrier material (e.g., **808 nm** for InP)
- **No fine tuning** needed

Pros
- Simple and reliable to implement
- High photon emission rates

Limitations:
- Poor photon coherence
- High background noise and jitter

b) Quasi-resonant

Laser Requirements:
- **Precisely tuned** to QD **p-shell transition**
  Requires **moderate spectral precision** (within ~1 nm)

Pros:
- Better **photon purity** and **indistinguishability** than above-band
- Lower background fluorescence

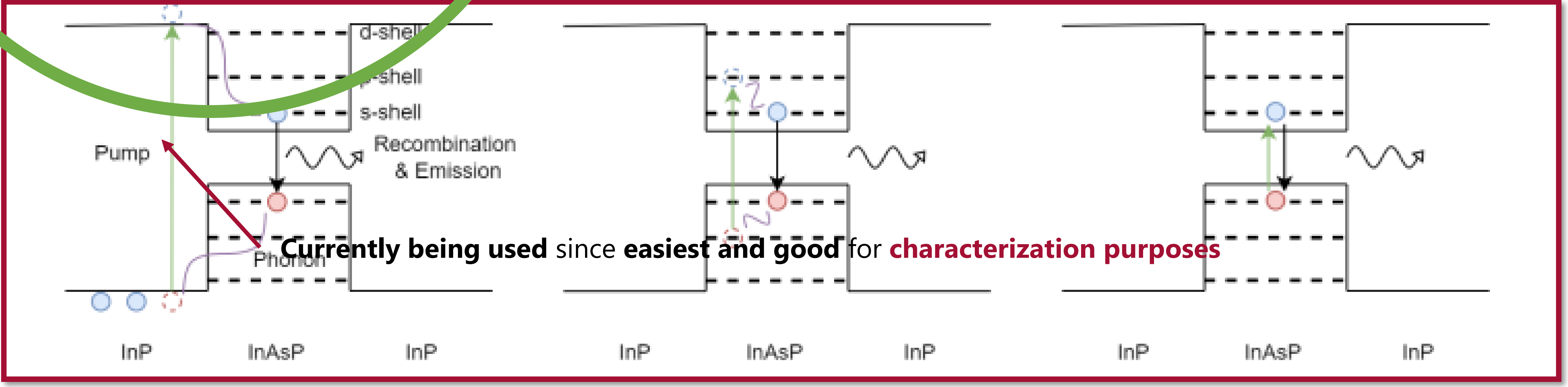
Limitations:
- Some jitter due to relaxation
- Laser tuning must match QD excitation level

c) Resonant

Laser Requirements:
- **Precisely tuned** to QD **s-shell transition**
- Requires **narrow-linewidth laser** (precision ~MHz)

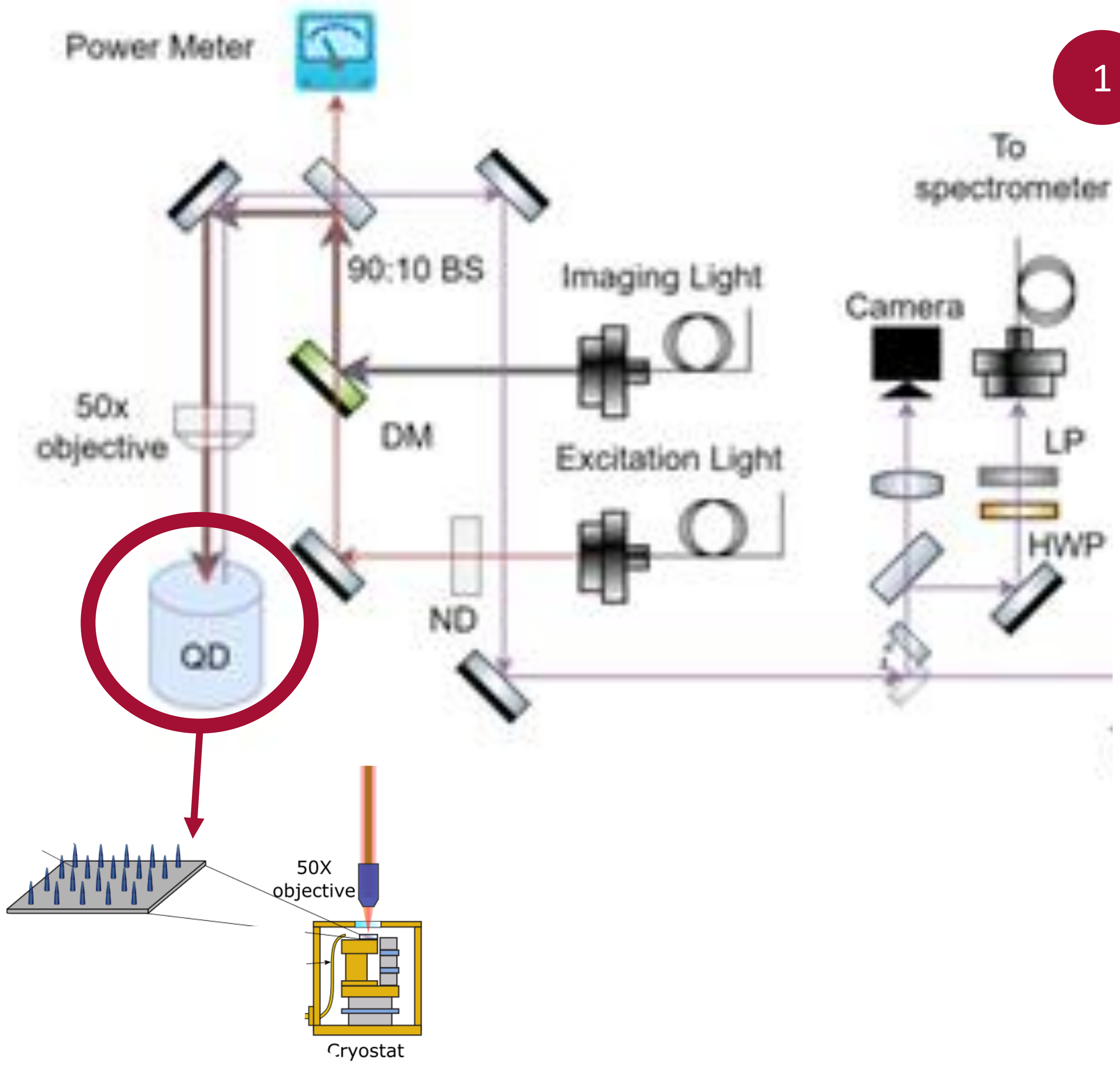
Pros:
- **Best photon coherence** and **indistinguishability**
- Ideal for **quantum interference** and **entanglement protocols**

Limitations:
- Technically complex (laser filtering, alignment)
- Requires active stabilization

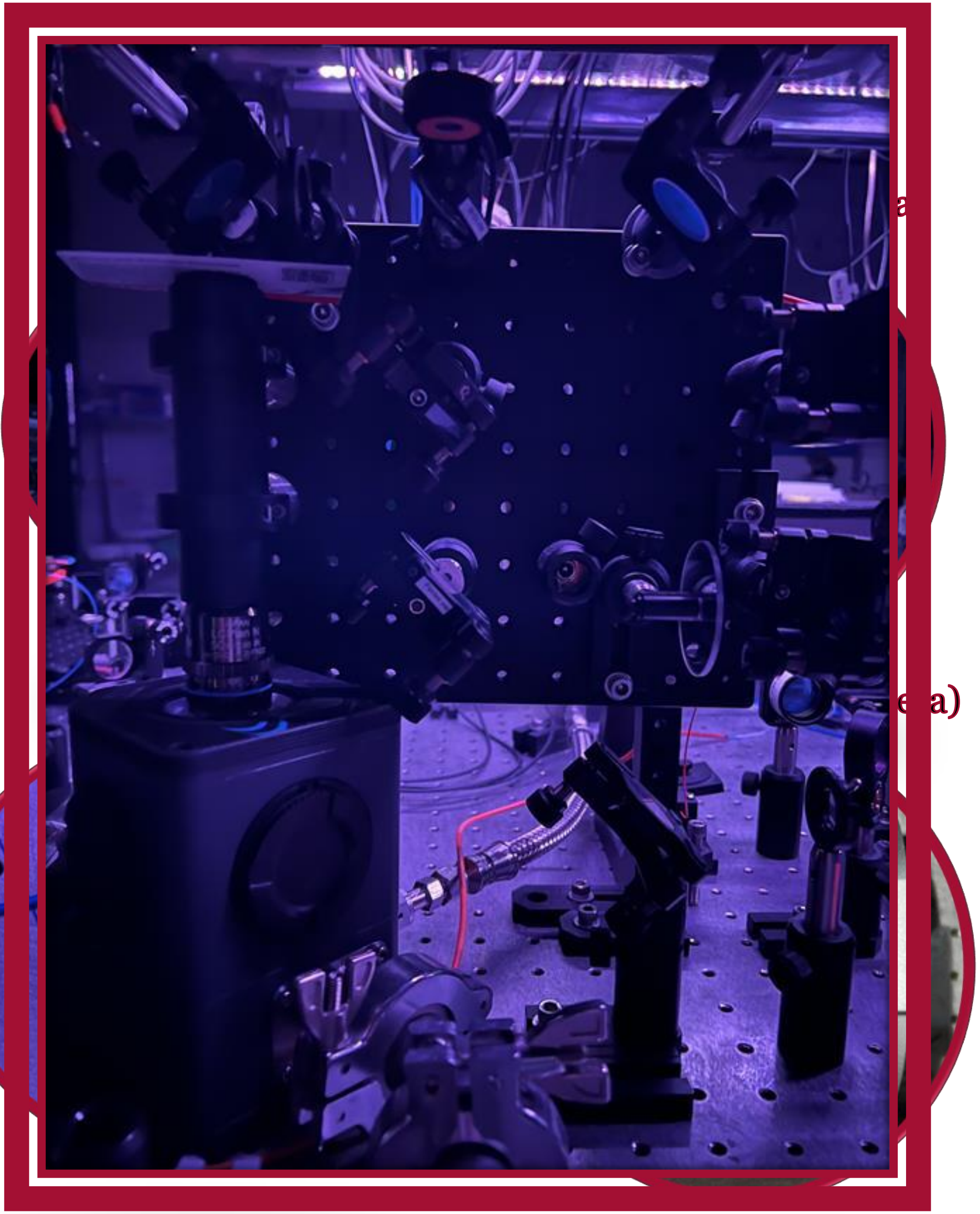


Currently being used since **easiest and good** for **characterization purposes**

Optical Setup



1



1. Li, M. (2024). *A quantum repeater sandbox with warm atomic memories and quantum dot photon sources* [Master's thesis, University of Waterloo]. UWSpace. https://hdl.handle.net/10012/21065

Spectrometer *Resolution Explained*

- Spectrometer **relies on diffraction grating** with three different faces; **1800, 1200 and 150 lines/mm face.**
  - **Higher groove density (1800 mm)** spreads **out light more**, translating to better separation between close wavelengths
  - **Lower groove density (150 mm)** spreads out light less, meaning wavelengths aren't well-defined

2

Image Scale

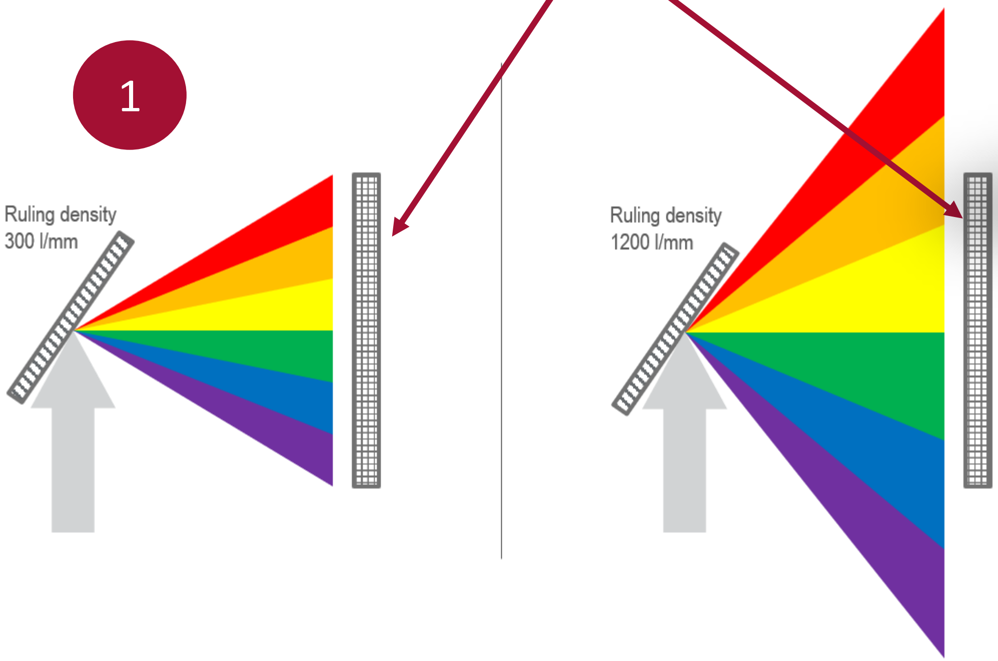
1800 lines/mm: 1pm /pixel

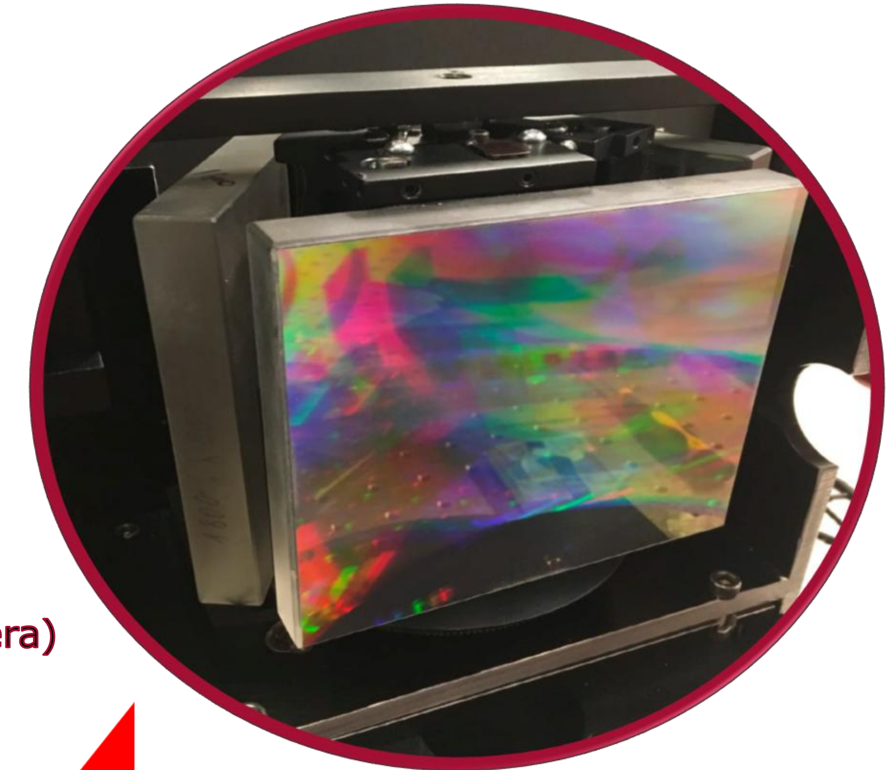
1200 lines/mm: 2 pm/pixel

150 lines/mm: 16 pm/pixel

Spectrometer (ASI Camera)

1





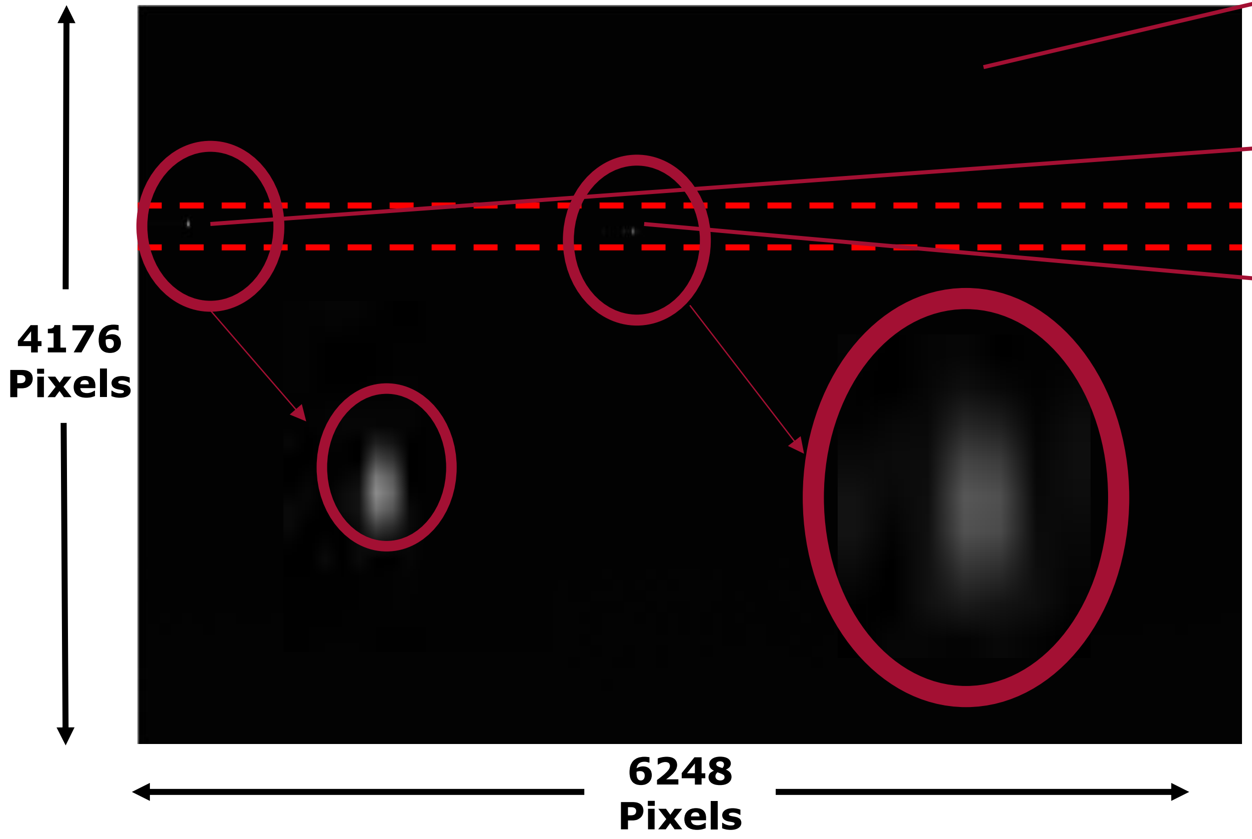
Triple Diffraction Grating

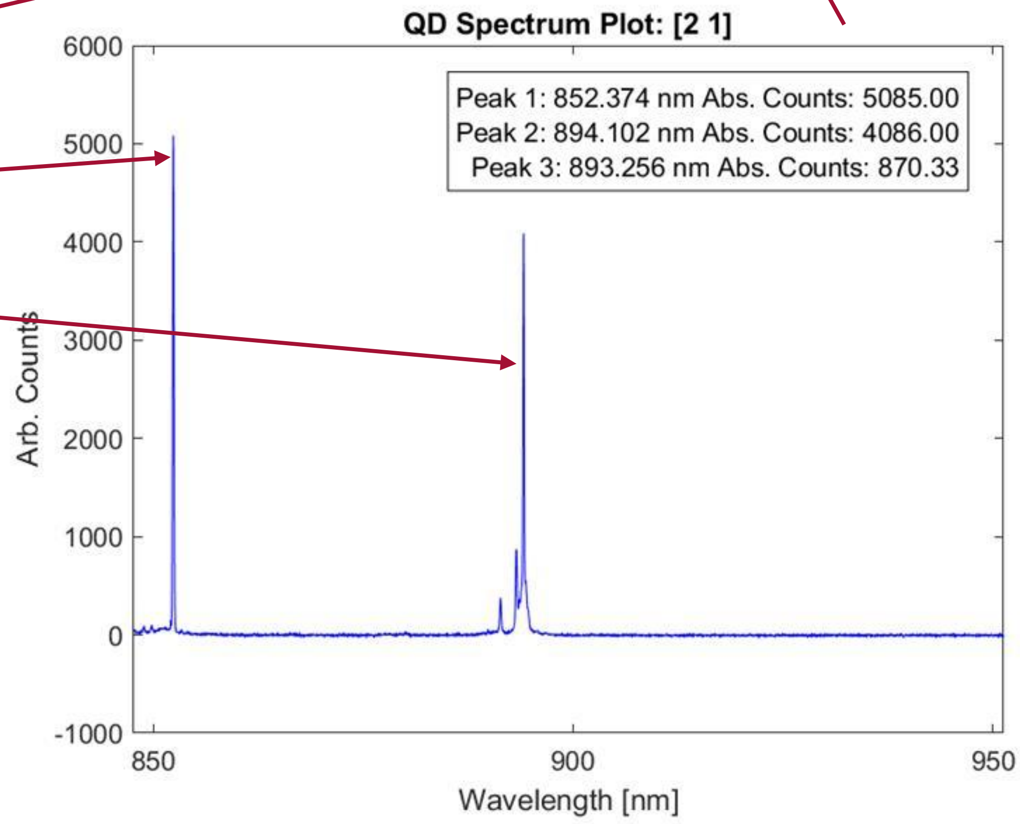
1. Google Images
2. Home-built low-cost high-resolution multigrating spectrometer for quantum optics with atomic ensembles and quantum dots

How does the Spectrometer Work (Basics)

- Incoming light is dispersed into its component wavelengths using our diffraction grating.
- The dispersed light forms a two-dimensional spectral image on the camera sensor.
  - **6248 pixels in width by 4176 pixels in height**
- To obtain the spectrum, the pixel values in each column are summed across all rows. This process collapses the two-dimensional image into a one-dimensional spectrum, displaying **Arb. Counts** versus **wavelength**.

Raw ASI image alongside it's respective **spectrum plot for [2 1]** at the **1200 mm grating**



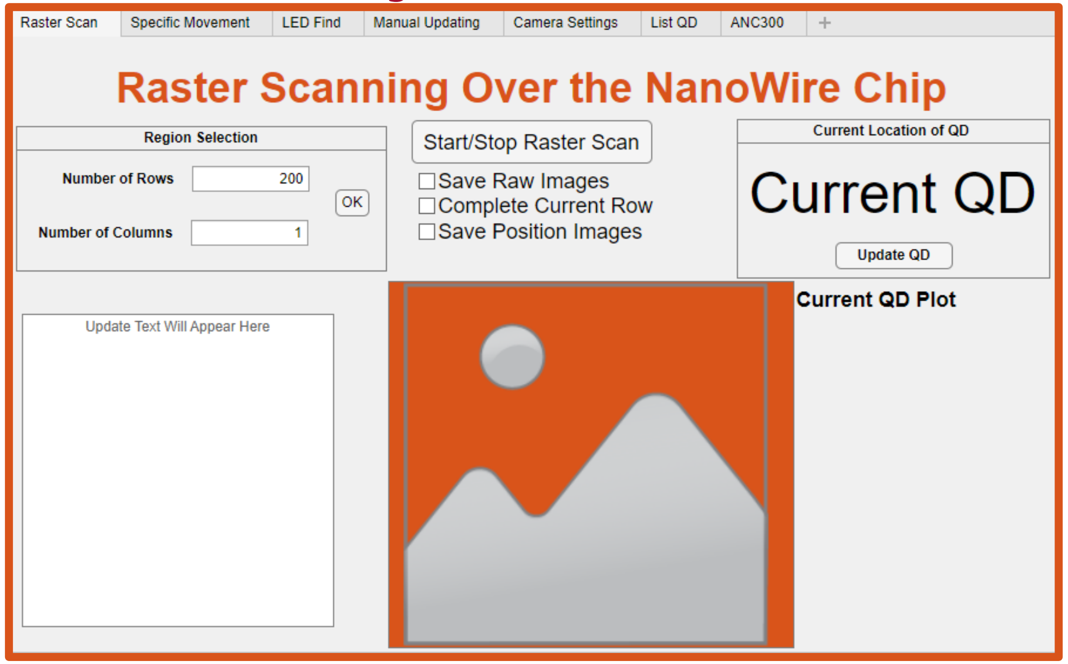


Raster Scan Overview

Need for Automation

- QDs are grown on a chip (**200x200 grid-like pattern)**
- **40,000 possible QD** emit~895 nm wavelength photons
- **Photons wavelengths**: Standard Deviation of 5nm.
- Use **1200 or 150 line/mm** diffraction grating, better for characterization

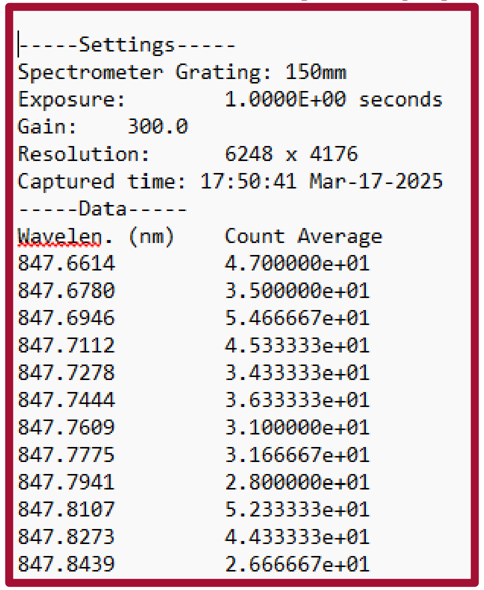
UI Tab for Controlling Raster Scan



Data Saved

- QD **spectrum plots and text files** saved by **default** with the
- User can **optionally opt** to save **raw QD spectrum** and **white light images**
- **Refer to examples below for QD [2 1]**

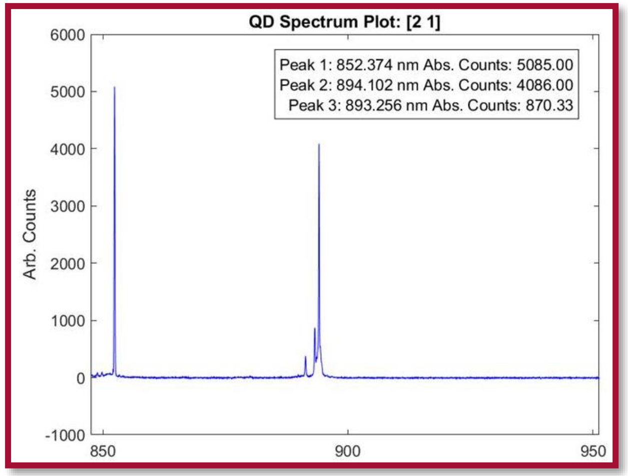
Text File Data (Always)



```
-----Settings-----
Spectrometer Grating: 150mm
Exposure:        1.0000E+00 seconds
Gain:     300.0
Resolution:      6248 x 4176
Captured time: 17:50:41 Mar-17-2025
-----Data-----
Wavelen. (nm)     Count Average
847.6614          4.700000e+01
847.6780          3.500000e+01
847.6946          5.466667e+01
847.7112          4.533333e+01
847.7278          3.433333e+01
847.7444          3.633333e+01
847.7609          3.100000e+01
847.7775          3.166667e+01
847.7941          2.800000e+01
847.8107          5.233333e+01
847.8273          4.433333e+01
847.8439          2.666667e+01
```

Position Photo (Optional)

Spectrum Plot (Always)



Raw Spectrometer Image (Optional)

Data/Results

- **Total data collected: 50 columns**
- **Data analyzed: 7466 QDs (Columns 14-50)**
- 1 Column = 200 unique dots

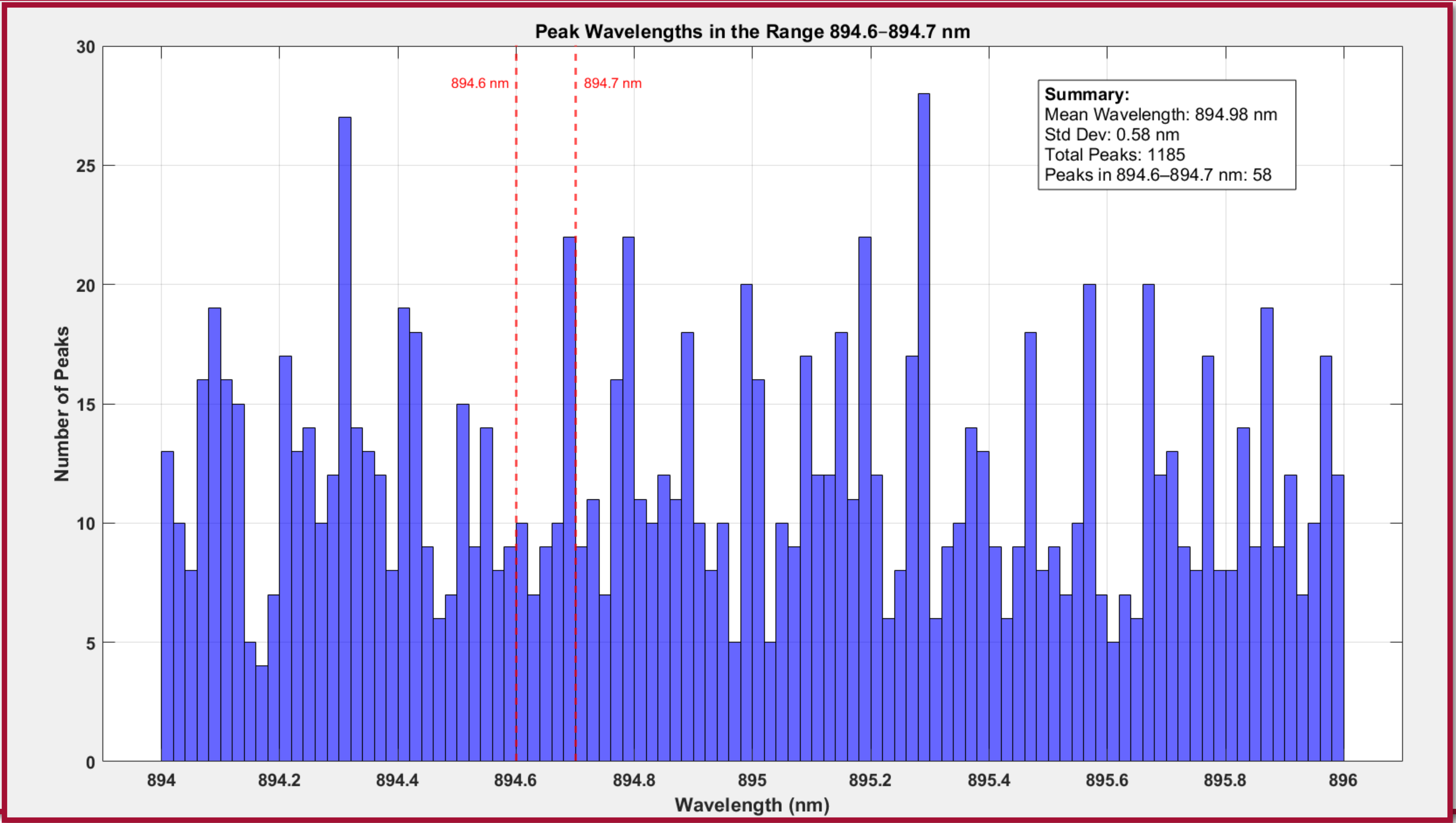
Data Collection Time Line

	From	To	Date	Comments	
		AUTOMATED SCANS WITH 150 ln/mm GRATING SUMMARY			
	[1 1]	[109 6]	06-03-2025	No reference (852 nm) signal ; Raster scan	
	[118 6]	[153 7]	10-03-2025	No reference (852 nm) signal ; Raster scan	
	[157 7]	[144 14]	11-03-2025	No reference (852 nm) signal ; Raster scan	
	[1 2]	[98 4]	21-03-2025	With reference (852 nm) signal; List scan; *Note -*	
	[98 4]	[148 14]	24-03-2025	With reference (852 nm) signal; List scan; *Note -*	
9:44 hours	[140 14]	[146 22]	25-03-2025	With reference (852 nm) signal; Raster scan	~ 8 columns done
7:30 hours	[145 22]	[24 28]	26-03-2025	With reference (852 nm) signal; Raster scan	~ 6.5 columns done
9:47 hours	[24 28]	[1 37]	27-03-2025	With reference (852 nm) signal; Raster scan	~ 8 columns done
2:32 hours	[1 37]	[31 39]	28-03-2025	With reference (852 nm) signal; Raster scan	~ 2 columns done
5:34 hours	[1 39]	[84 43]	01-04-2025	With reference (852 nm) signal; Raster scan	~ 4.25 columns done
8:00 hours	[85 43]	[1 50]	02-04-2025	With reference (852 nm) signal; Raster scan	~ 7.5 columns done
				Finished 50 columns (10,000) QD: 1/4 Mark	

Data/Results

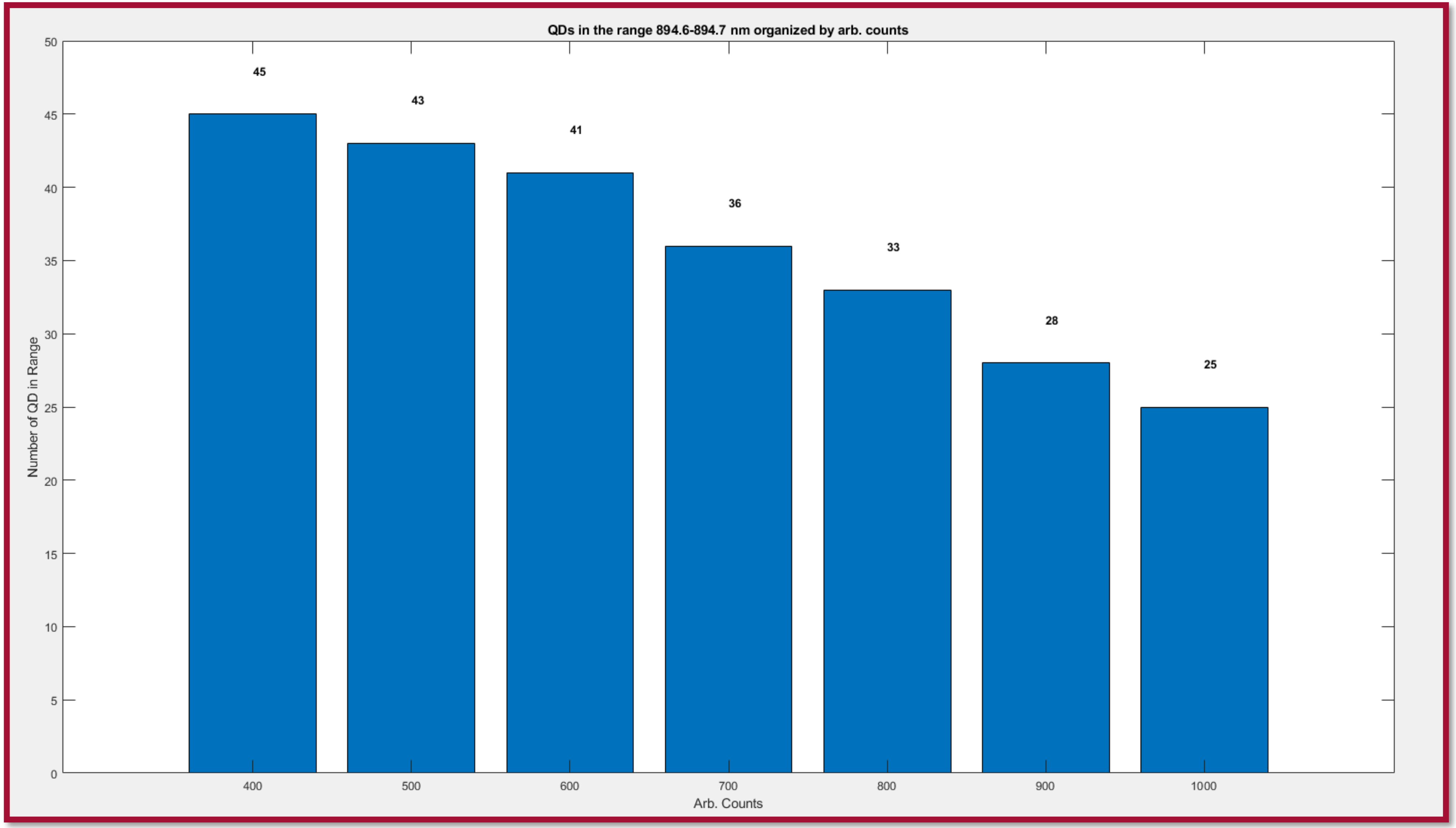
This Histogram has a peak cut off of 300 Counts

Number of Peaks

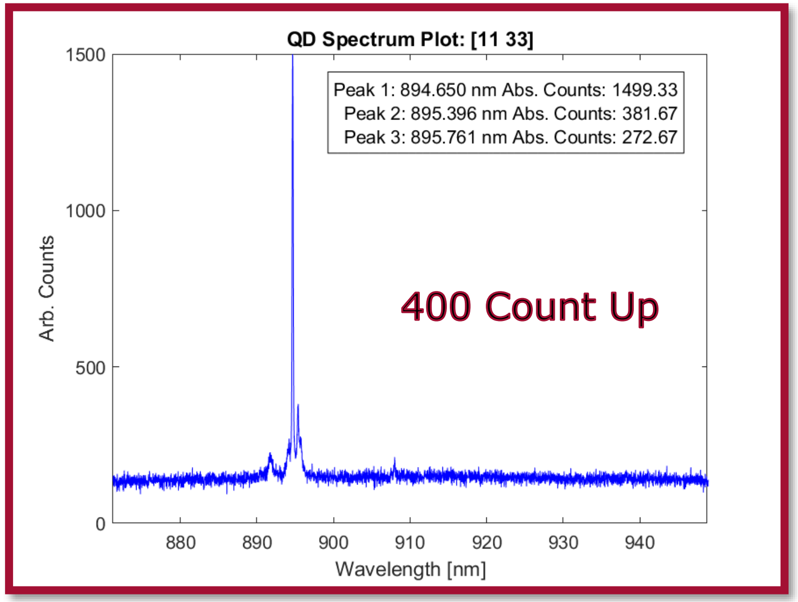


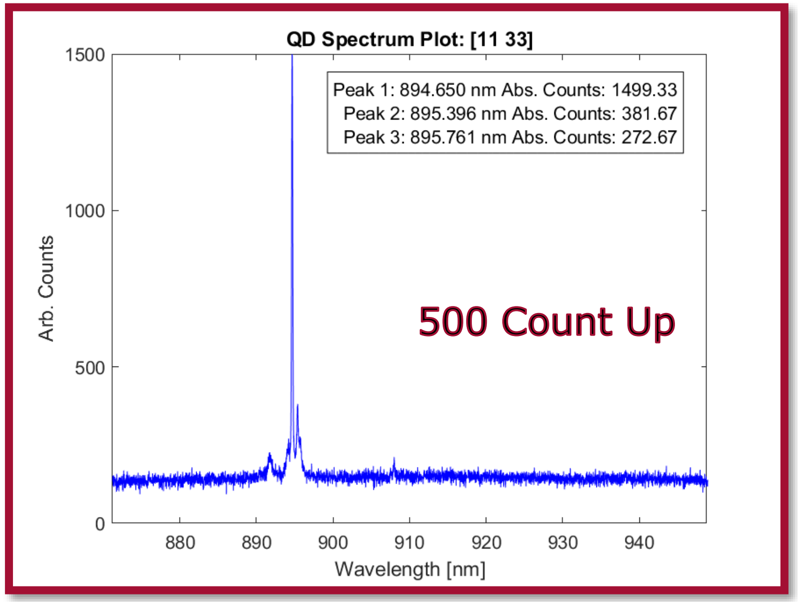
Wavelength (nm)

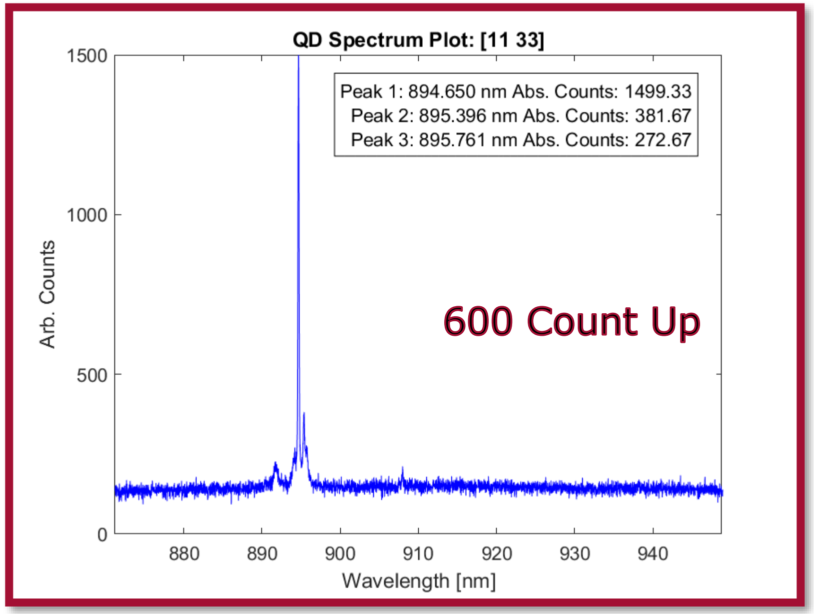
Data/Results

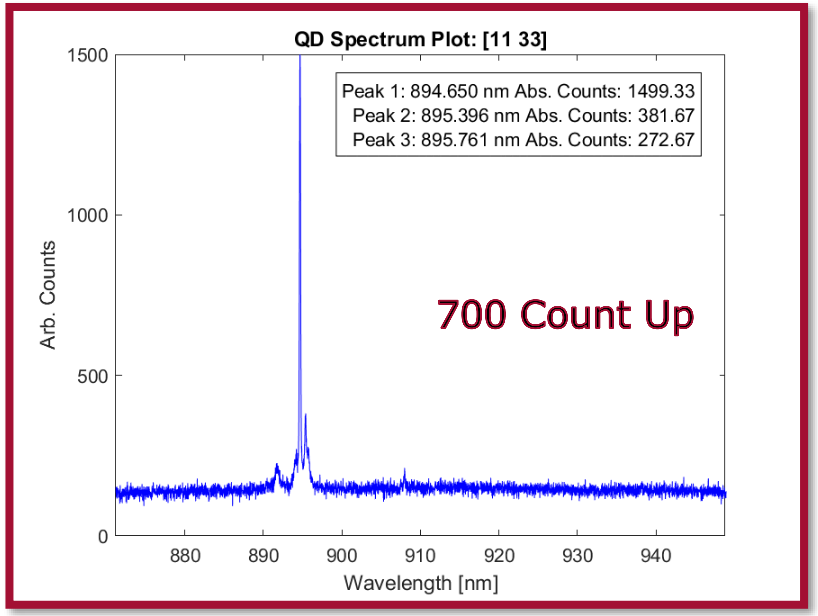


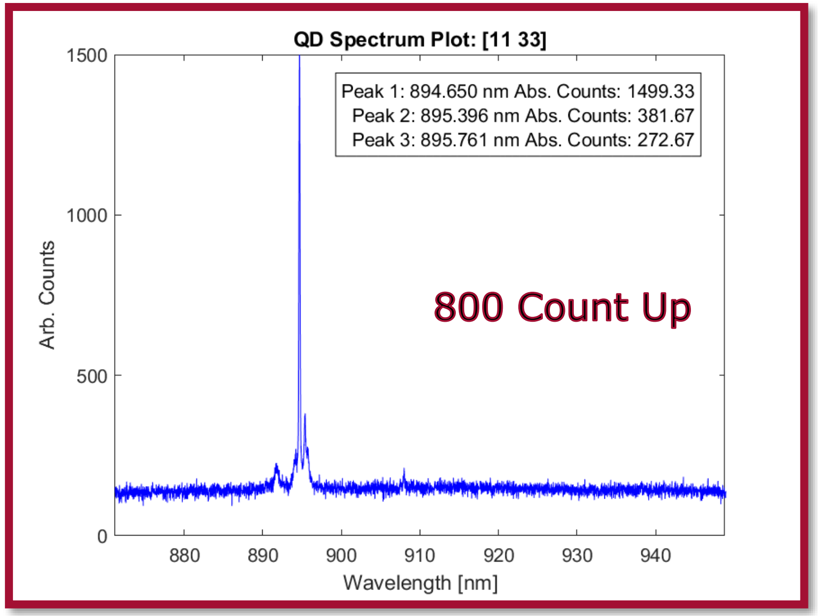
Data/Results

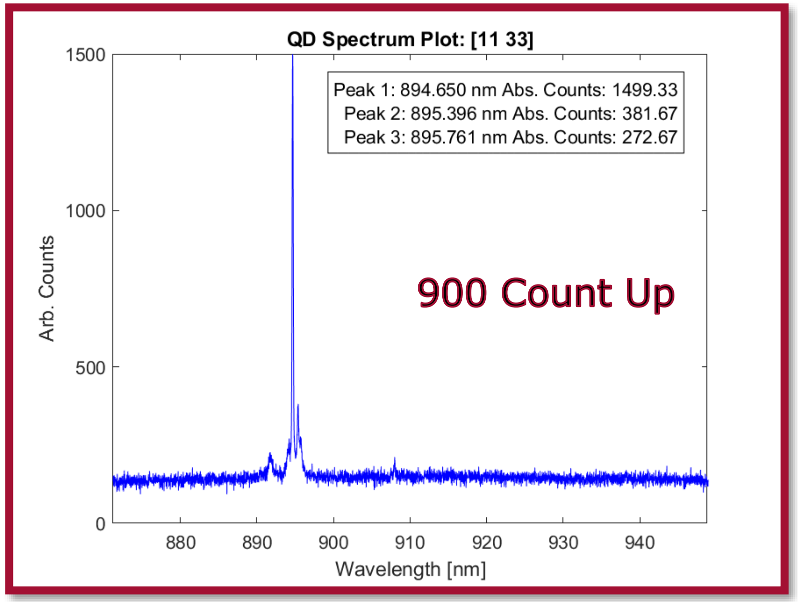








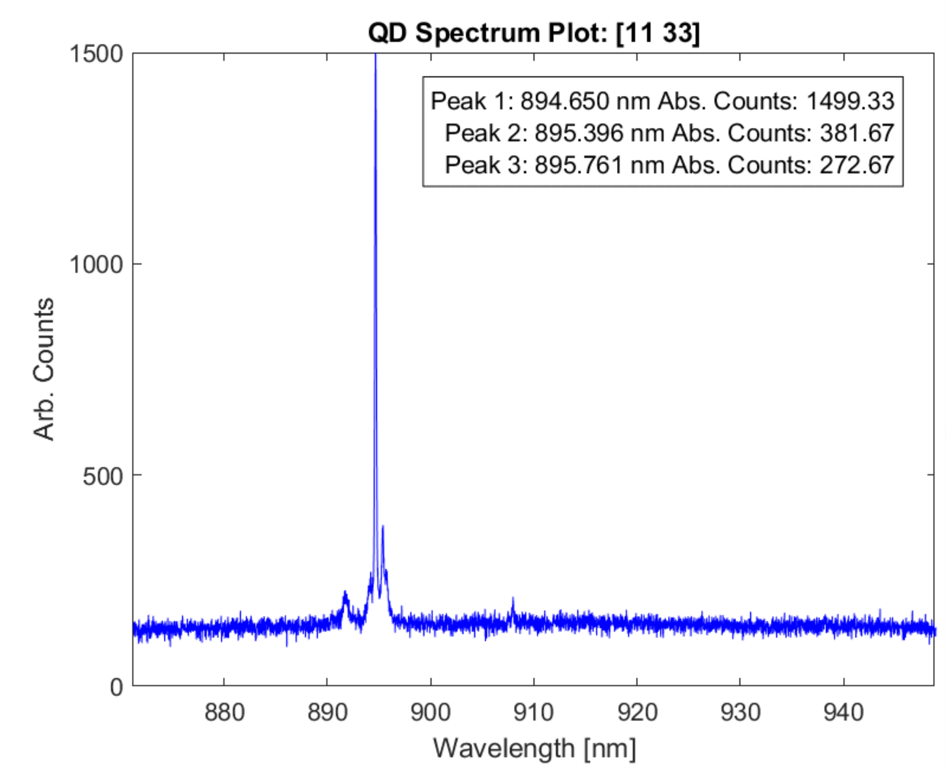


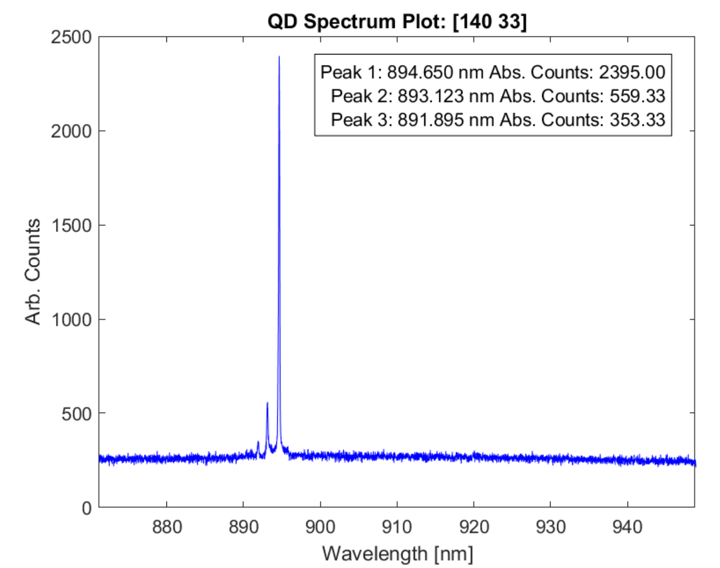


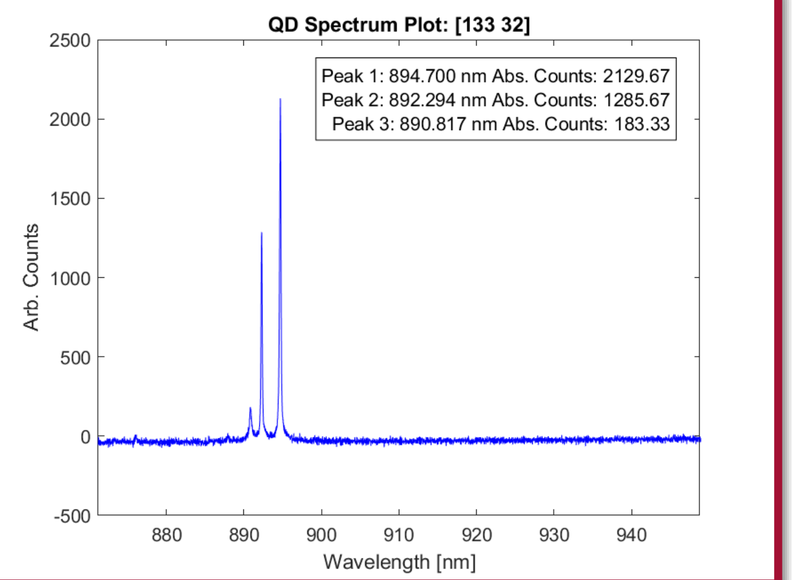
Data/Results

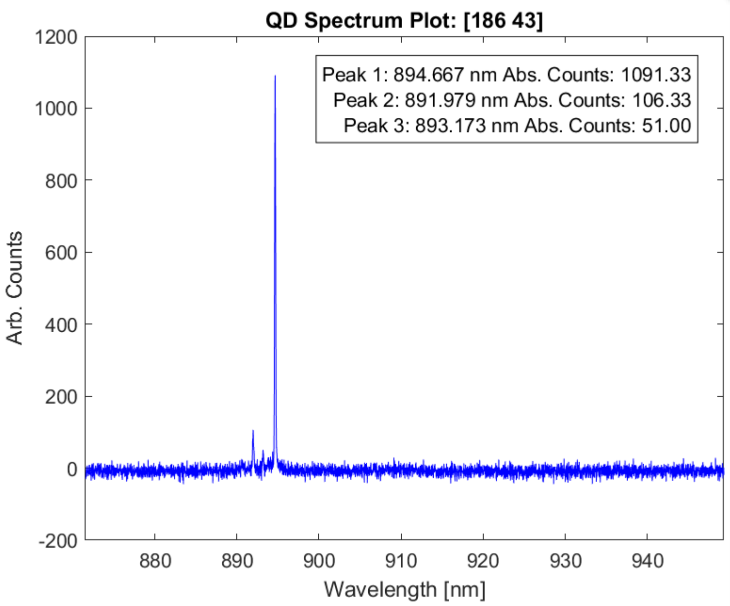
Plots that Stood Out

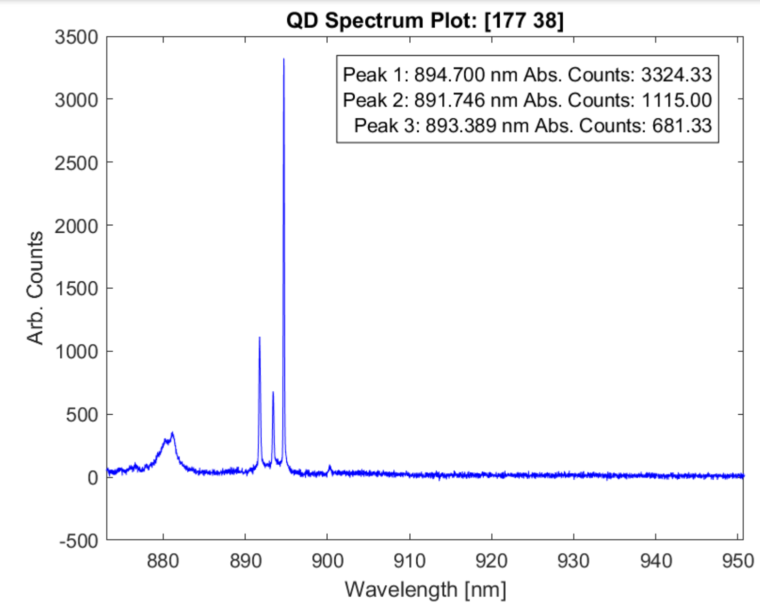
1000 Count Up (Golden Stuff)



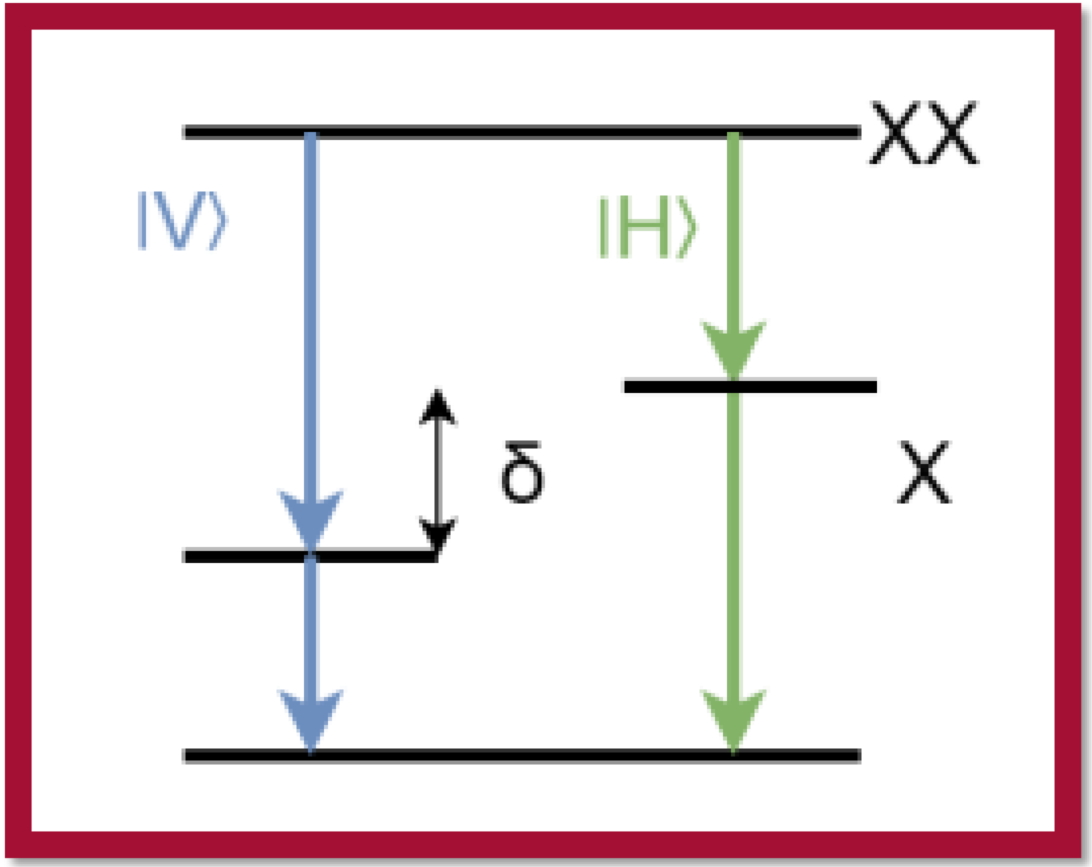








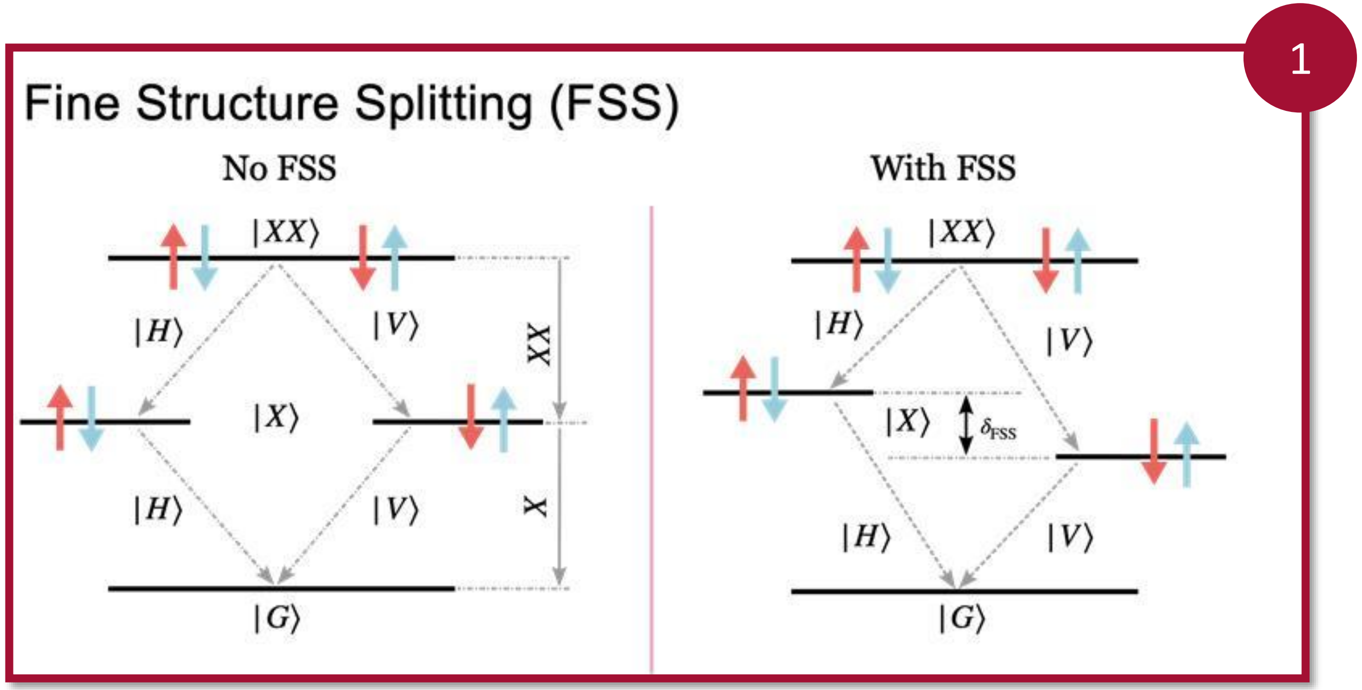
Fine Structure Splitting (FSS) Overview



Where $\delta = FSS\ Energy$

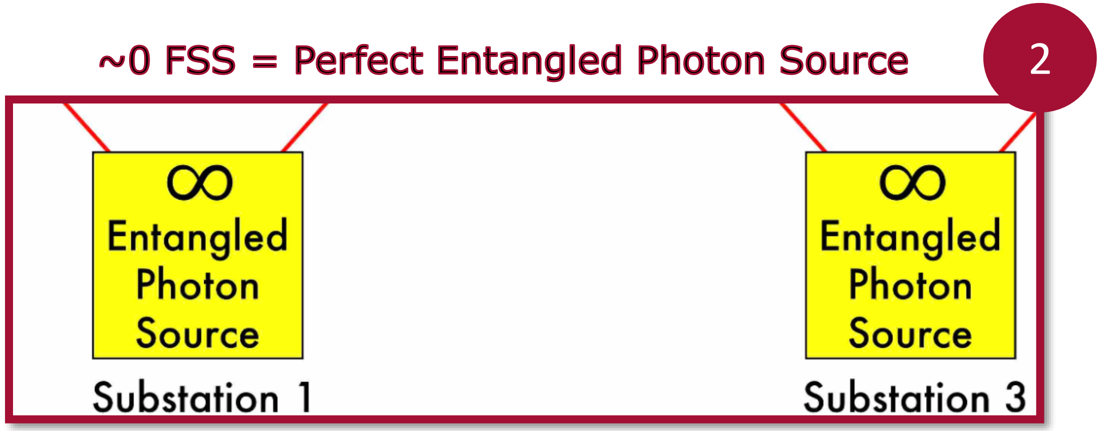
What is FSS?

- Electron-pair recombination leads to **horizontal or vertical polarization**.
- Exciton splits into **two slightly different energy states** depending on the polarization orientation **(FSS energy)**



Why Care About FSS?

- **Entangled photon pairs** generated via **biexciton-exciton cascade.**
- Exciton states must be **degenerate** (same energy no matter polarization orientation)
- Ideal case, finding a **QD with zero FSS**



1. Fine Structure Splitting of Quantum Dots By Katie McDonnel
2. Figuero Research Group

Calculating FSS

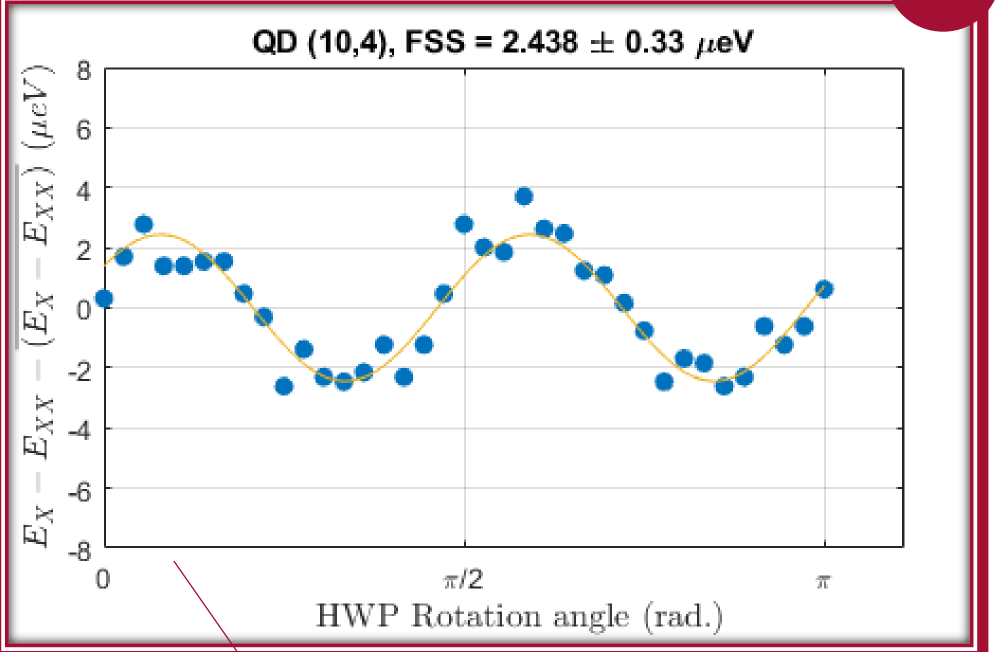
FSS Concept: Fine-structure splitting (FSS) changes QD eigenstates from circular to rectilinear.

Peak Shift Measurement: Exciton (E_x) and biexciton (E_{xx}) peak shifts recorded for different polarizations.

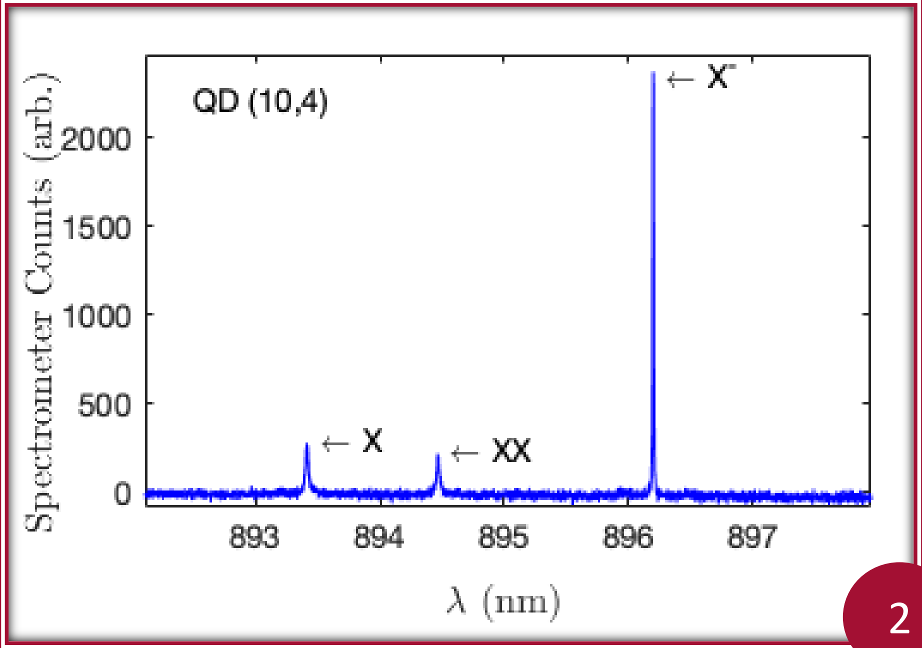
Data Analysis: (Ex - Exx) differences plotted against polarization angle.

FSS Extraction: Amplitude of a fitted cosine function gives the FSS value.

1



The axis would actually be from 0 to 2pi



2

1. Katie Quantum Logbook
2. Katie Quantum Logbook

Process to Gather FSS Data

Manual/Old Method

1. Navigate to the quantum dot (QD) of interest using the piezoelectric driver, ensuring precise but gradual positioning.

2. **Utilize the live spectrometry script** *(FWHM_ver_Richard.m)* to manually align the QD until the emission peak reaches sufficient intensity.

3. **Initiate rotation** of **the half-wave plate (HWP)** to monitor and record the wavelength shifts of the exciton and biexciton peaks.

4. Repeat the procedure for each **subsequent QD of interest.**

1

ANC 300 Piezo Driver

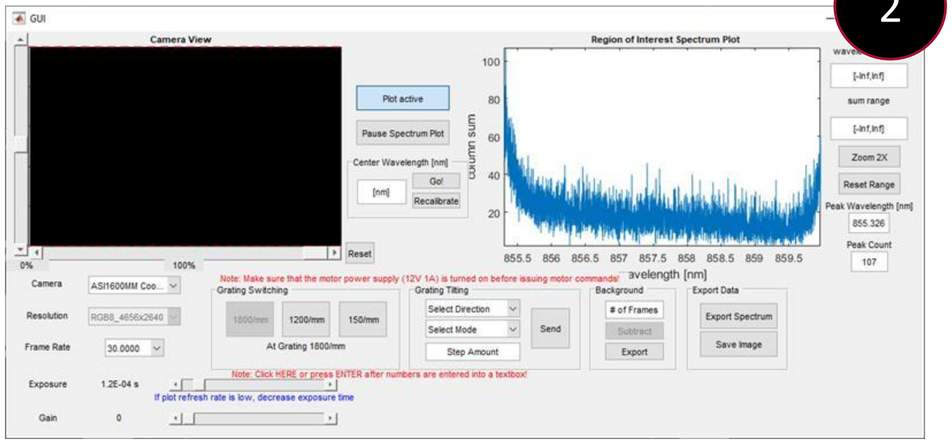
Yuck

Yucky

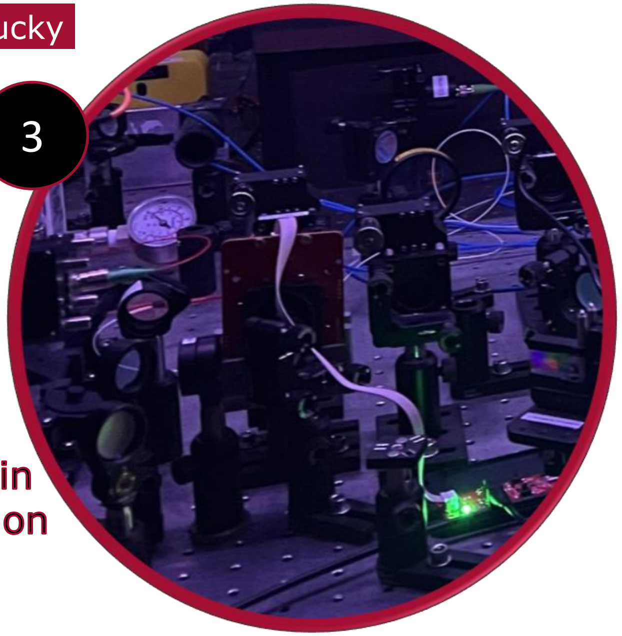
Yuckier

Live Spectrometry Script FWHM_Ver_Richard.m (Designed by Jackson and Richard)

2



3



HWP mounted in Thorlabs Rotation Mount

4

[105 16]
[11 33]
[133 32]
[139 21]
[140 33]
[141 22]
[144 35]
[150 35]
[154 16]
[154 22]
[167 38]
[169 38]
[170 34]

Long Tedious list of QDs of Interest

1. Google Images

Process to Gather FSS Data

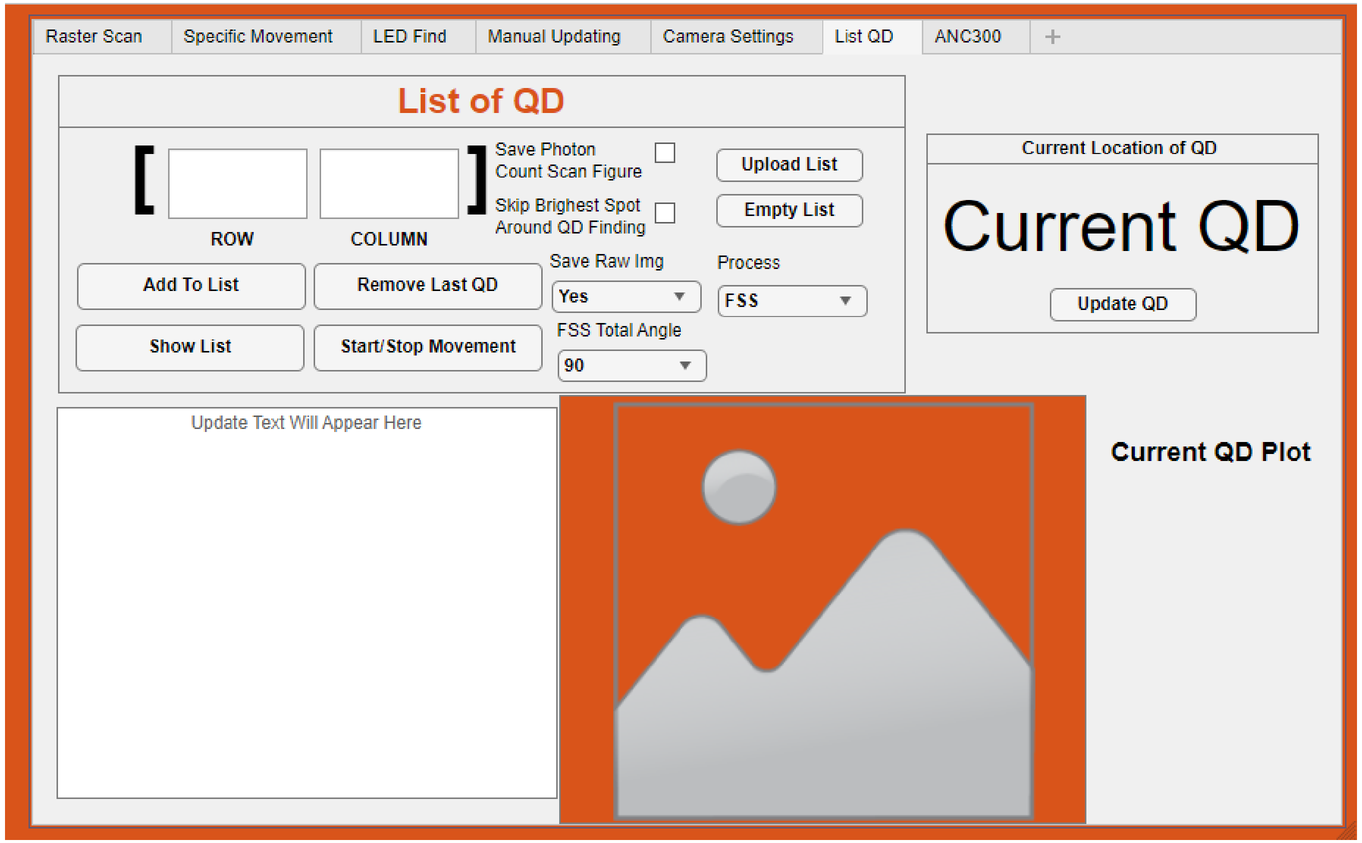
Automated/Improved Method

1. Select **QD manually via row/column input** *or* upload a list via text file using the **Upload List** button
2. Click **Show List** to view and confirm selected QDs
3. In the **Process** section:

   Select **FSS**

   Choose desired total angle: **90°, 180°, 270°, or 360°**
4. Click **Start/Stop Movement** to begin the process and watch it work its magic

UI Tab for Controlling FSS



Creating FSS Plots

- Both Manual and Automated FSS methods require data processing to achieve the **desired FSS plots**
- Requires an important component; **exciton and biexciton identification**

How to Identify Exciton and Biexciton

Exciton (X) and Charged Exciton (X^+ / X^-)

- Both Emission intensity follows a **quadratic** dependence on power (**$I \propto P^2$**). (Linear at low power)
- **X** is differentiated from **X^- as** usually X^- is more redshifted (lower energy)

Biexciton (XX)

- Emission intensity increases **linearly** with excitation power (**$I \propto P^1$**).

Legend

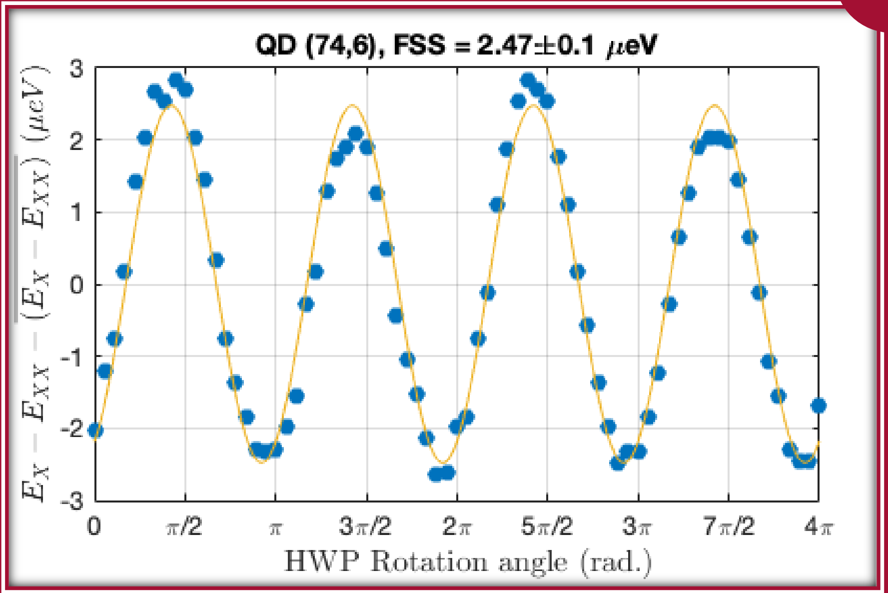
Exciton

Biexciton

Charged Exciton

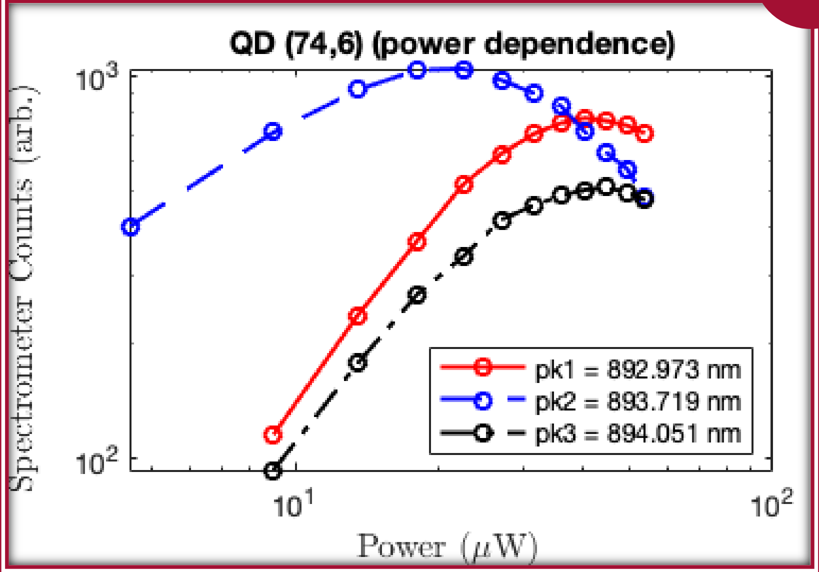
FSS Plot for [74 6]

1



Power Dependence Plot for [74 6]

2



1. Katie Quantum Logbook
2. Katie Quantum Logbook

Data/Results

- Identified and compiled a **list of 23 quantum dots** (QDs)
  - ➢ Selection based on **proximity to cesium D1 transition wavelength**
  - ➢ Prioritized QDs with **high photon count rates**
- Noted **discrepancies compared to 150 mm grating raster scan**
- 13 Spectra scans completed
- 4 full FSS measurements completed on the following QDs:
  - ➢ **[35 36]**
  - ➢ **[74 46]**
  - ➢ **[175 24]**
  - ➢ **[194 27]**

Wavelength Difference from closest Energy Level

```
[[1 31]] | Peak: 894.583 nm | Count: 483.33 | Δ: 0.005 nm | Completion Status: Spectra Done (Peak at 894.884nm, bad)
[[7 20]] | Peak: 894.583 nm | Count: 1307.33 | Δ: 0.005 nm | Completion Status: Spectra Done (Peak at 894.905nm, bad)
[[74 46]] | Peak: 894.583 nm | Count: 2892.00 | Δ: 0.005 nm | Completion Status: Spectra and FSS Done (overlap for both)
[[111 22]] | Peak: 894.567 nm | Count: 498.00 | Δ: 0.011 nm | Completion Status: Spectra Done (weak peak, 894.713nm)
[[175 24]] | Peak: 894.567 nm | Count: 1643.67 | Δ: 0.011 nm | Completion Status: Spectra and FSS Done (good peak, 894.733nm)
[[45 16]] | Peak: 894.567 nm | Count: 489.00 | Δ: 0.011 nm | Completion Status:
[[71 39]] | Peak: 894.567 nm | Count: 843.33 | Δ: 0.011 nm | Completion Status:
[[154 22]] | Peak: 894.600 nm | Count: 1143.67 | Δ: 0.022 nm | Completion Status: (overlap for both)
[[194 27]] | Peak: 894.600 nm | Count: 1054.00 | Δ: 0.022 nm | Completion Status: Spectra and FSS Done (overlap for both)
[[103 28]] | Peak: 894.550 nm | Count: 927.00 | Δ: 0.028 nm | Completion Status:
[[170 34]] | Peak: 894.617 nm | Count: 3540.33 | Δ: 0.012 nm | Completion Status: Spectra Done
[[38 24]] | Peak: 894.617 nm | Count: 683.67 | Δ: 0.012 nm | Completion Status:
[[57 32]] | Peak: 894.617 nm | Count: 632.67 | Δ: 0.012 nm | Completion Status: (really good)
[[35 36]] | Peak: 894.617 nm | Count: 2581.67 | Δ: 0.012 nm | Completion Status: Spectra and FSS Done (good peak, 894.748nm)
[[1 31]] | Peak: 894.583 nm | Count: 483.33 | Δ: 0.022 nm | Completion Status:
[[7 20]] | Peak: 894.583 nm | Count: 1307.33 | Δ: 0.022 nm | Completion Status: (really good)
[[150 35]] | Peak: 894.633 nm | Count: 2730.33 | Δ: 0.028 nm | Completion Status: Spectra Done
[[28 19]] | Peak: 894.633 nm | Count: 1820.33 | Δ: 0.028 nm | Completion Status:
[[55 23]] | Peak: 894.633 nm | Count: 679.33 | Δ: 0.028 nm | Completion Status:
[133 32]: Spectra Done
[140 33]: Spectra Done
[177 38]: Spectra Done
[186 43]: Spectra Done
```

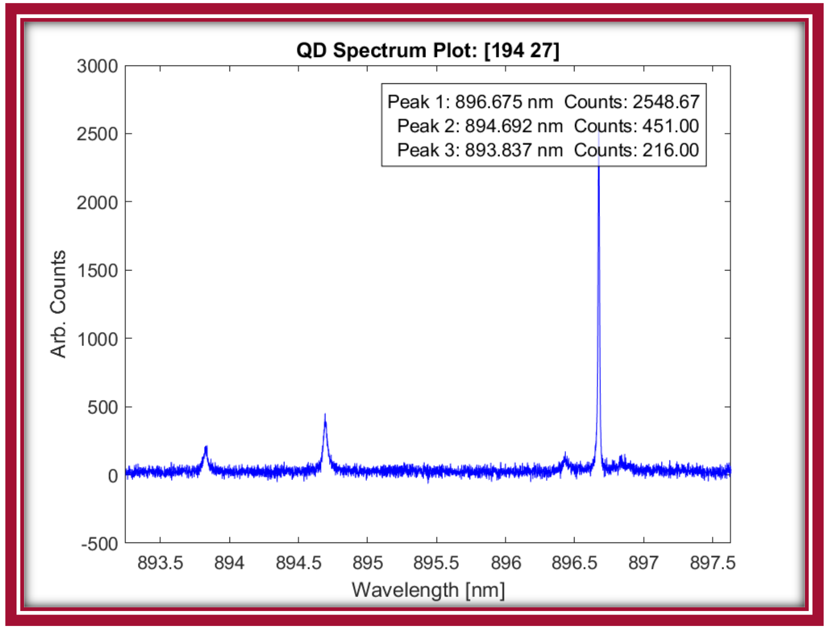
Discrepancy Filled Plots Part 1

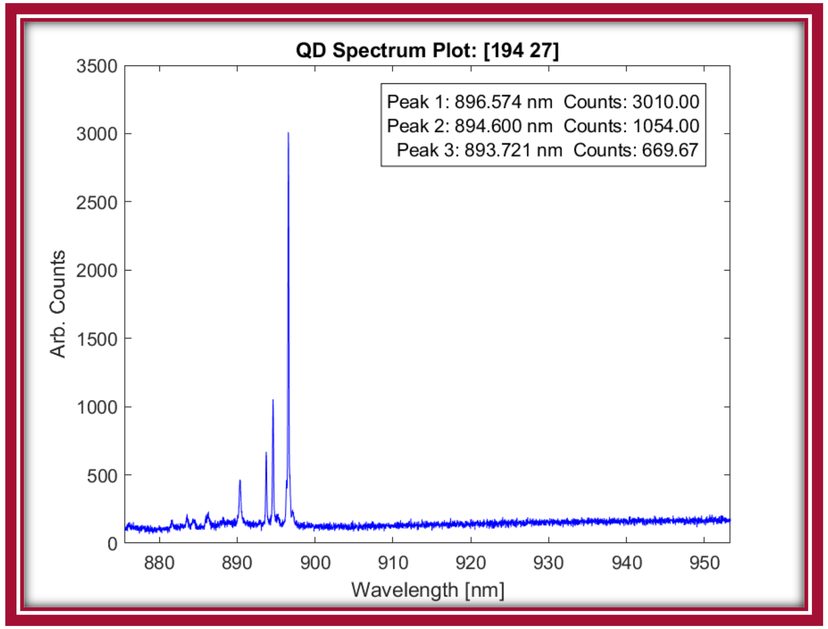
1800 lines/mm grating (Raster Scan)

150 lines/mm grating

Wavelength Difference Between Same Peaks of Interest

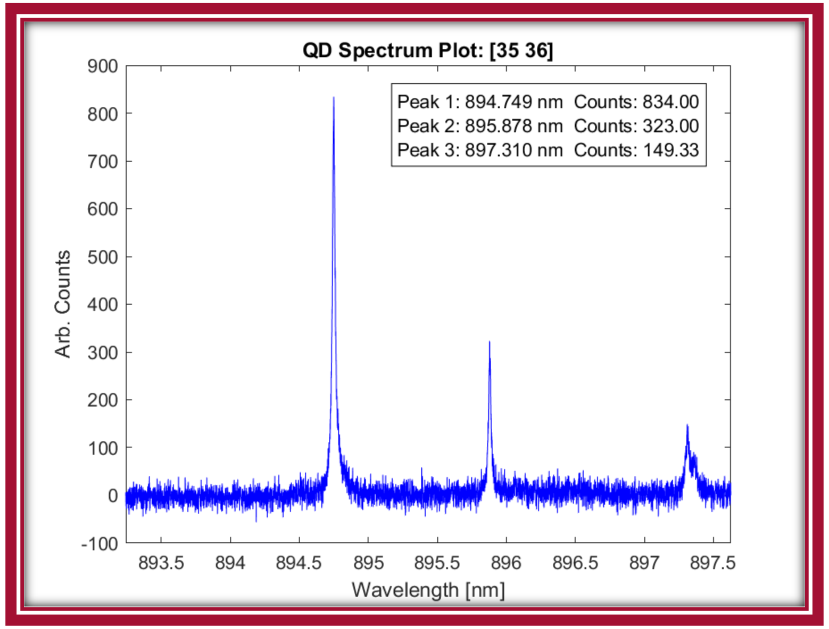
[194 7]

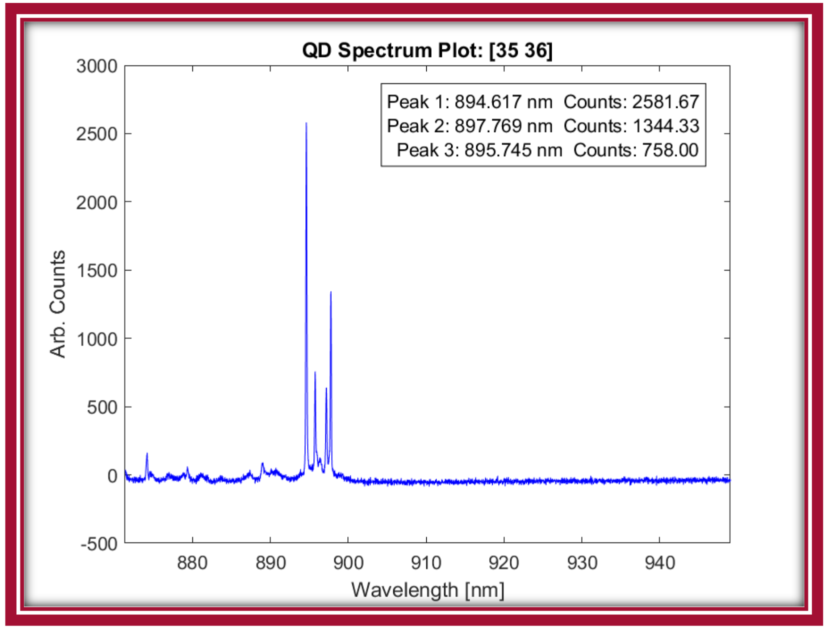




101 pm Peak 1
92 pm Peak 2

[35 36]





132 pm

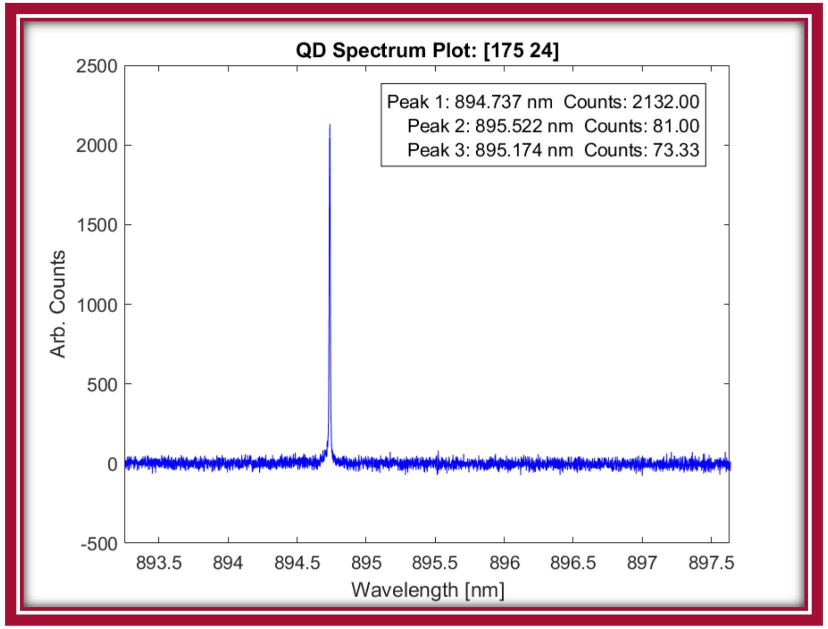
Discrepancy Filled Plots part 2

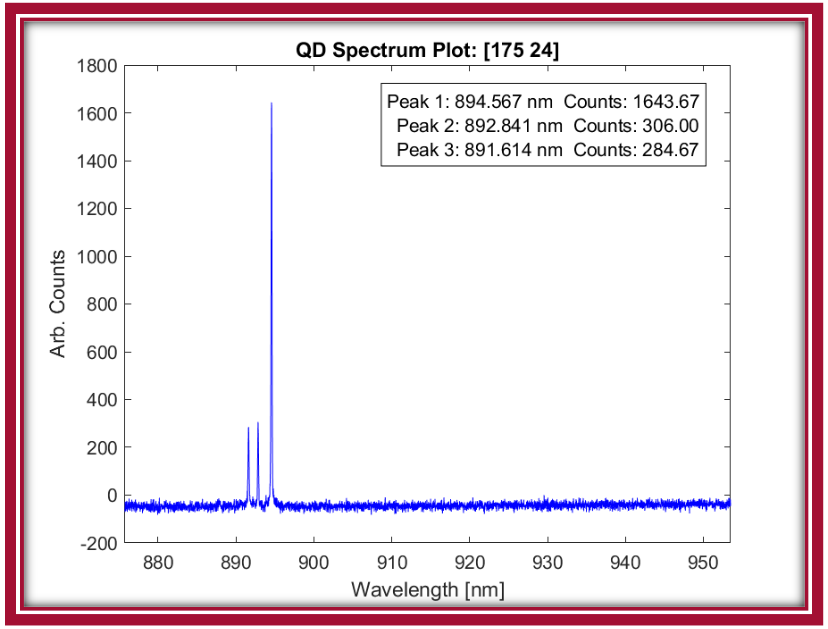
1800 lines/mm grating (Raster Scan)

150 lines/mm grating

Wavelength Difference Between Same Peaks of Interest

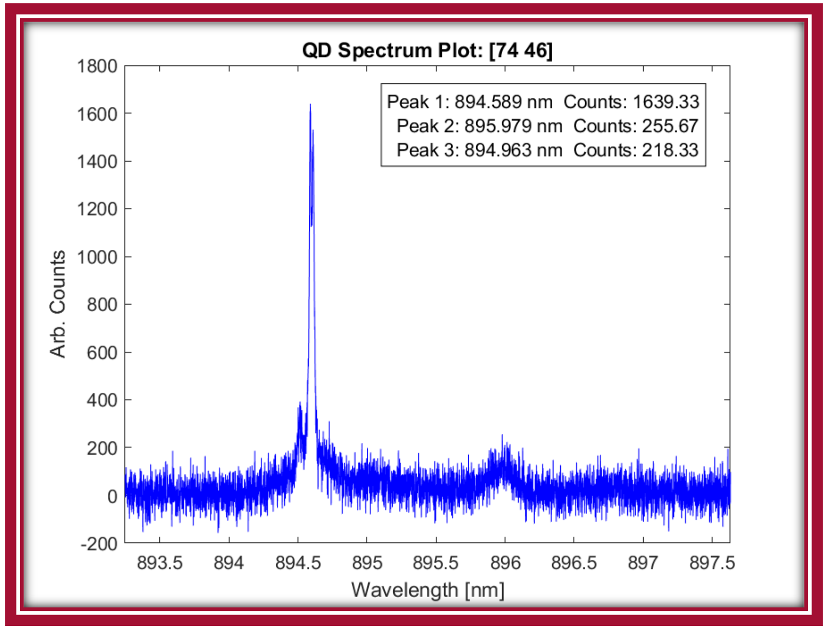
[175 24]

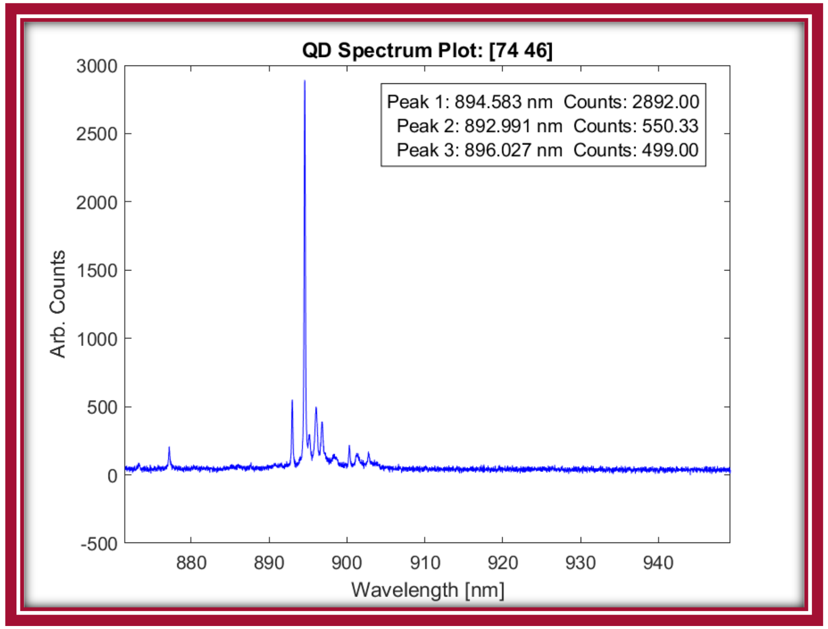




170 pm

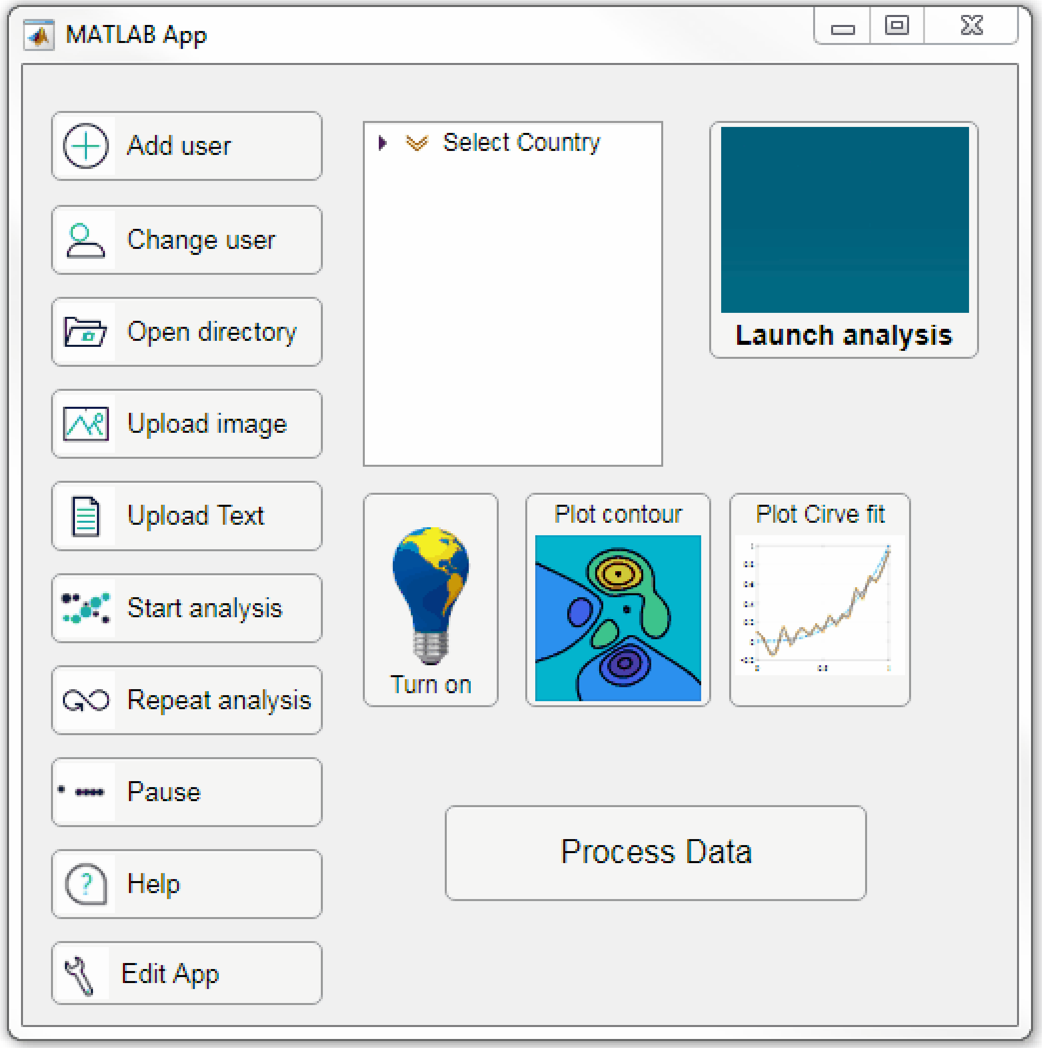
[74 46]





6 pm

NWQD Operation Application Overview

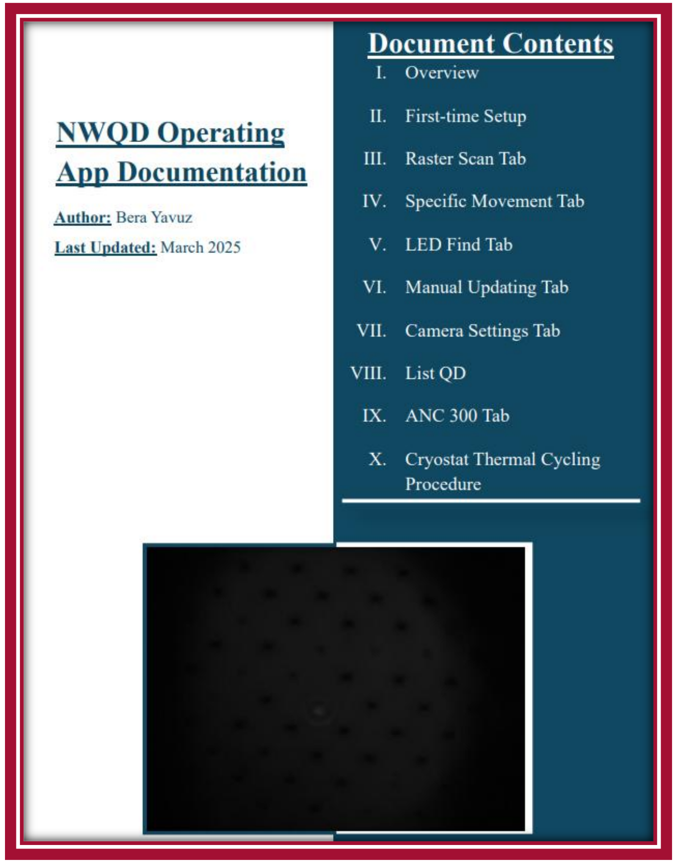


Overview

- **Actual file name: NWQD_Operating_App.mlapp**
    - Where, **NWQD** stands for **Nano-wire Quantum Dots**
- Sophisticated NWQD application that offer 7 different tabs;

I. Raster Scan
II. Specific Movement
III. LED Find
IV. Manual Updating
V. Camera Settings
VI. List QD
VII. ANC300

- Saves QD position and selected Region of Interest for Spectrometer Camera Between Sessions
- For more information **Refer to the 12-page Documentation**

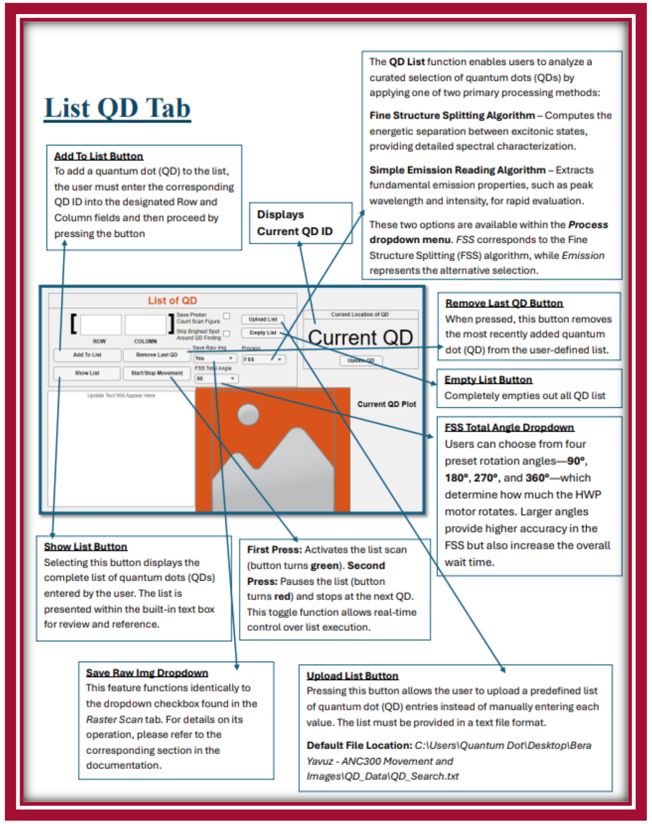

NWQD Operating App Documentation

Author: Bera Yavuz

Last Updated: March 2025

Document Contents

Title Page


List QD Tab

Add To List Button
To add a quantum dot (QD) to the list, the user must enter the corresponding QD ID into the designated Row and Column fields and then proceed by pressing the button

Displays Current QD ID

The **QD List** function enables users to analyze a curated selection of quantum dots (QDs) by applying one of two primary processing methods:

Fine Structure Splitting Algorithm – Computes the energetic separation between excitonic states, providing detailed spectral characterization.

Simple Emission Reading Algorithm – Extracts fundamental emission properties, such as peak wavelength and intensity, for rapid evaluation.

These two options are available within the ***Process* dropdown menu**. *FSS* corresponds to the Fine Structure Splitting (FSS) algorithm, while *Emission* represents the alternative selection.

Remove Last QD Button
When pressed, this button removes the most recently added quantum dot (QD) from the user-defined list.

Empty List Button
Completely empties out all QD list

FSS Total Angle Dropdown
Users can choose from four preset rotation angles—**90°**, **180°**, **270°**, and **360°**—which determine how much the HWP motor rotates. Larger angles provide higher accuracy in the FSS but also increase the overall wait time.

Show List Button
Selecting this button displays the complete list of quantum dots (QDs) entered by the user. The list is presented within the built-in text box for review and reference.

First Press: Activates the list scan (button turns **green**). **Second Press:** Pauses the list (button turns **red**) and stops at the next QD. This toggle function allows real-time control over list execution.

Save Raw Img Dropdown
This feature functions identically to the dropdown checkbox found in the *Raster Scan* tab. For details on its operation, please refer to the corresponding section in the documentation.

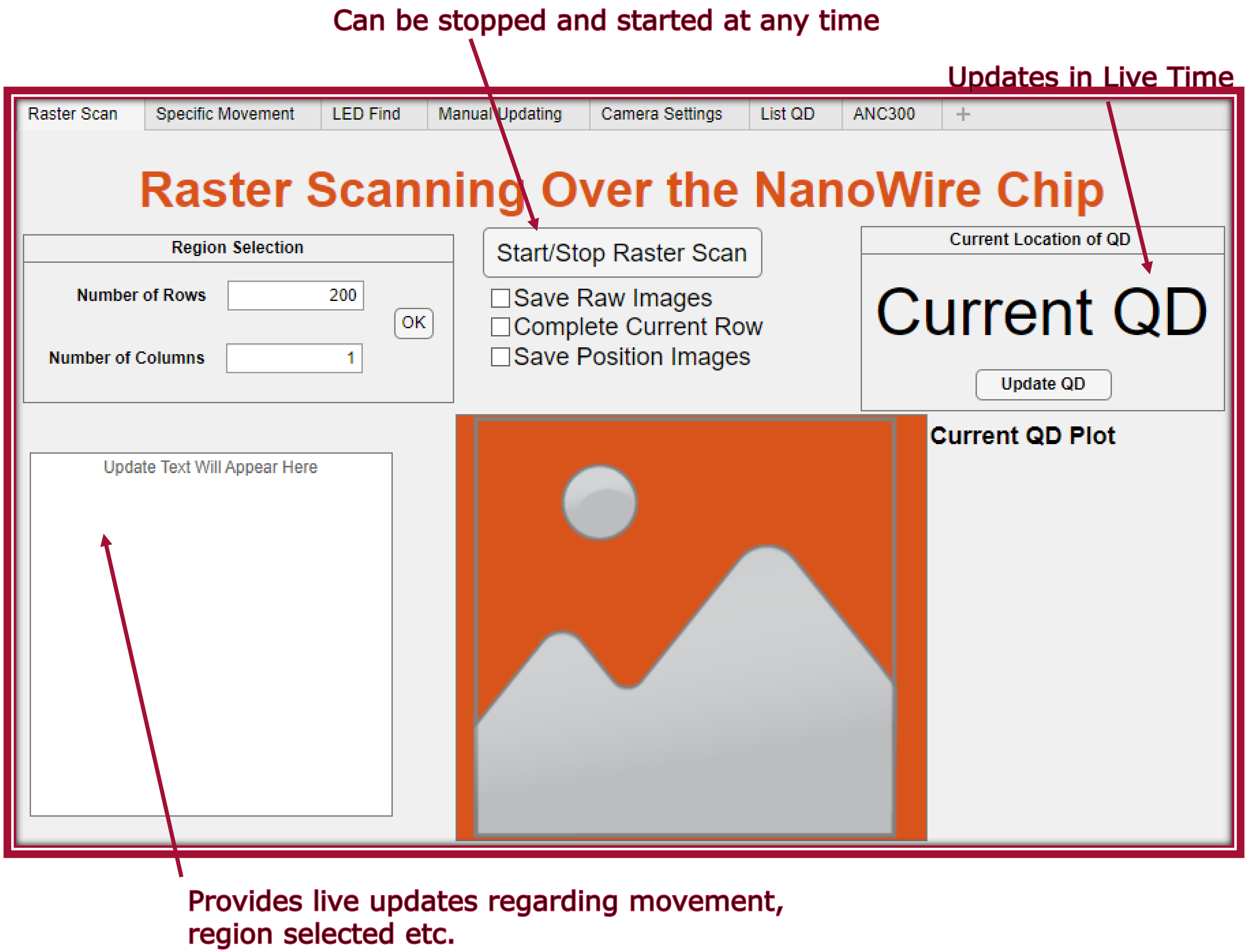
Upload List Button
Pressing this button allows the user to upload a predefined list of quantum dot (QD) entries instead of manually entering each value. The list must be provided in a text file format.

Default File Location: *C:\Users\Quantum Dot\Desktop\Bera Yavuz - ANC300 Movement and Images\QD_Data\QD_Search.txt*

Example of a Detailed Overview of a function

Raster Scan Tab

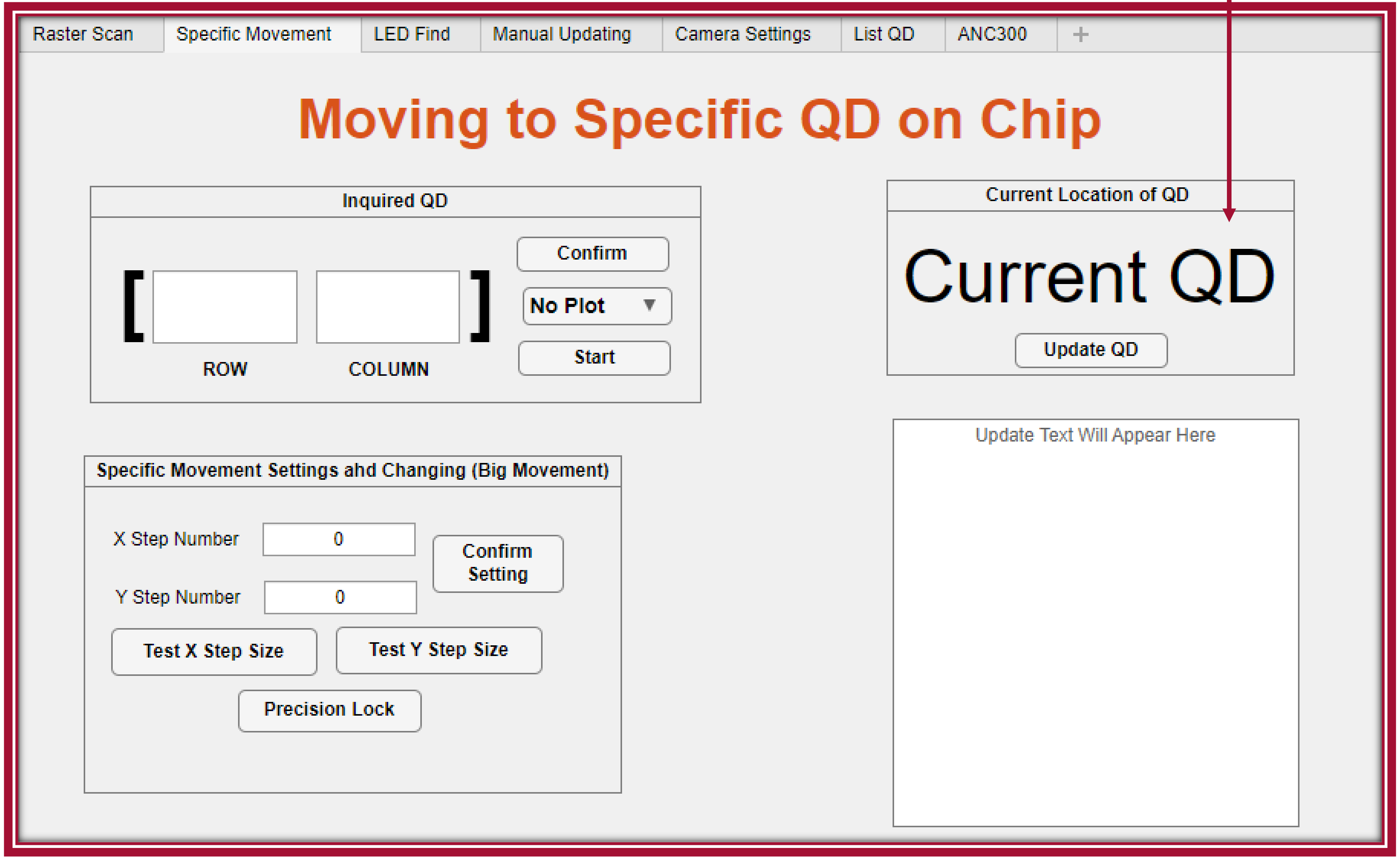
- Offers User Friendly approach of **raster scanning a desired QD region**



Specific Movement Tab

- Offers User Friendly approach of **moving to an inquired QD**
- Useful when user is in the **middle of the nanowire chip,** would normally have to go back to [1 1] or other known reference spot

Updates in Live Time



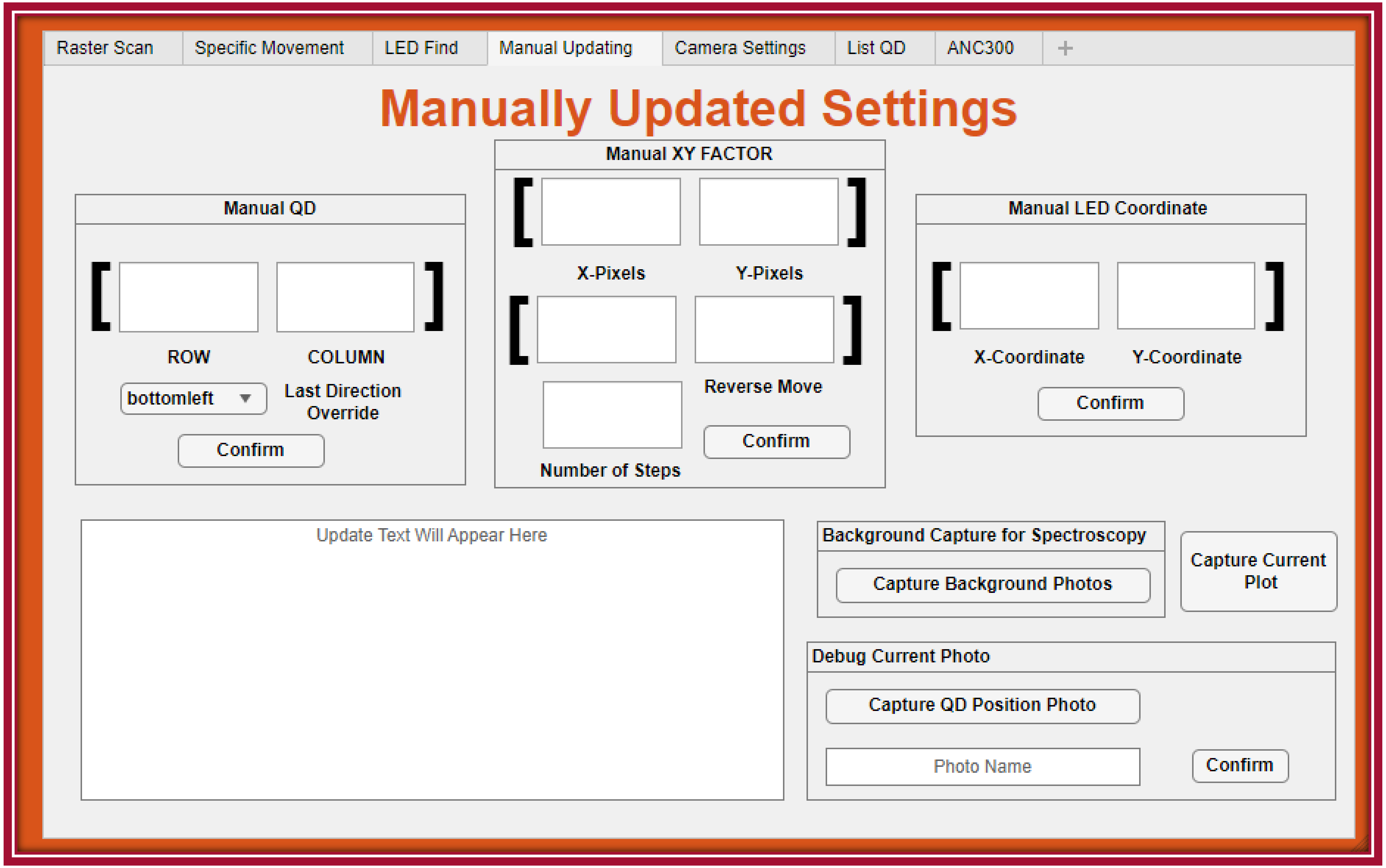
LED Find Tab

Raster Scan
Specific Movement
LED Find
Manual Updating
Camera Settings
List QD
ANC300
LED Coordinate Finder
IMPORTANT NOTE: Make sure to open Ueye Camera and slightly move until excitation laser is very visible and not being deformed due to a QD
Original Image
First Filter
Blob detected as LED
Original Image
Filtered Image
The coordinates of the excitation laser is [1230.916,1021.679]

Manual Updating Tab

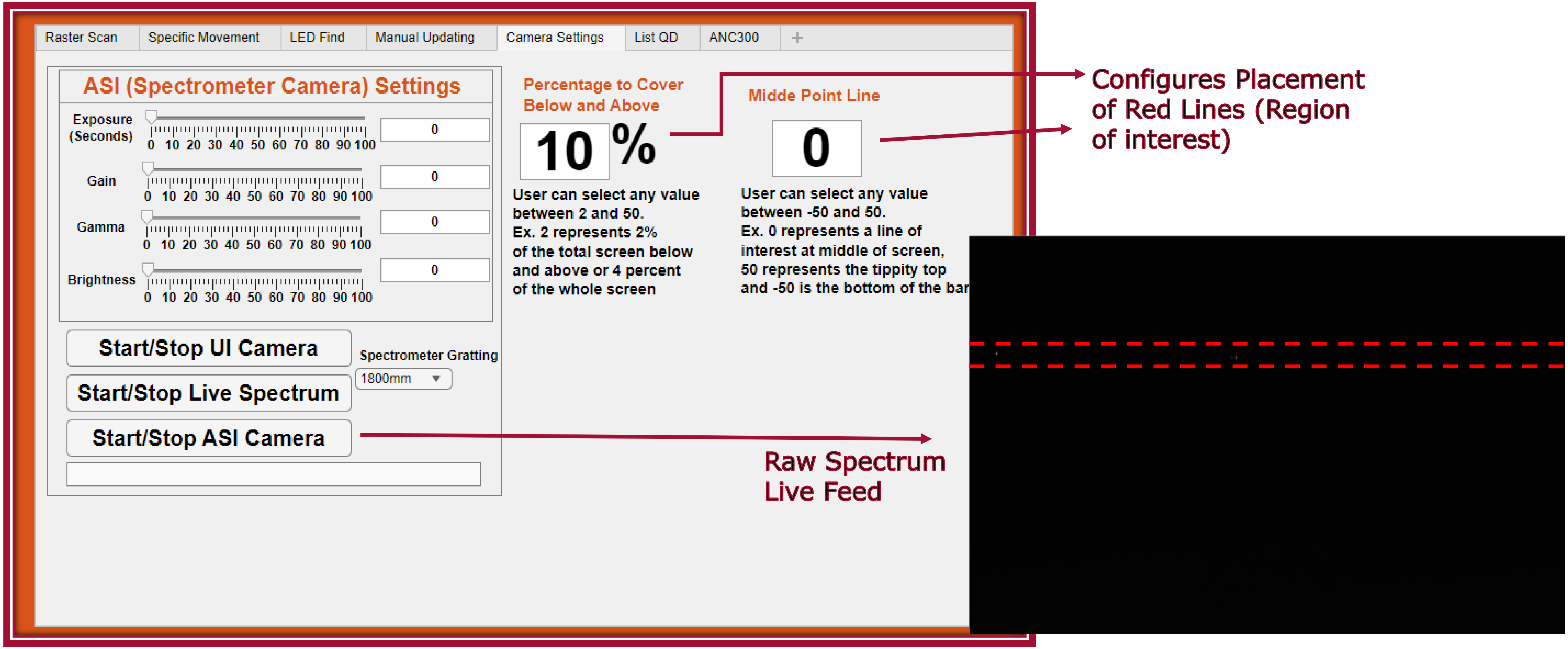
- Manual XY Factor Panel crucial for the **function of whole app**
  - **Needs updating** when **cryostat is cycled**

- Typically, will only need to update **Manual QD panel**
  - Only done if user decides to manually move



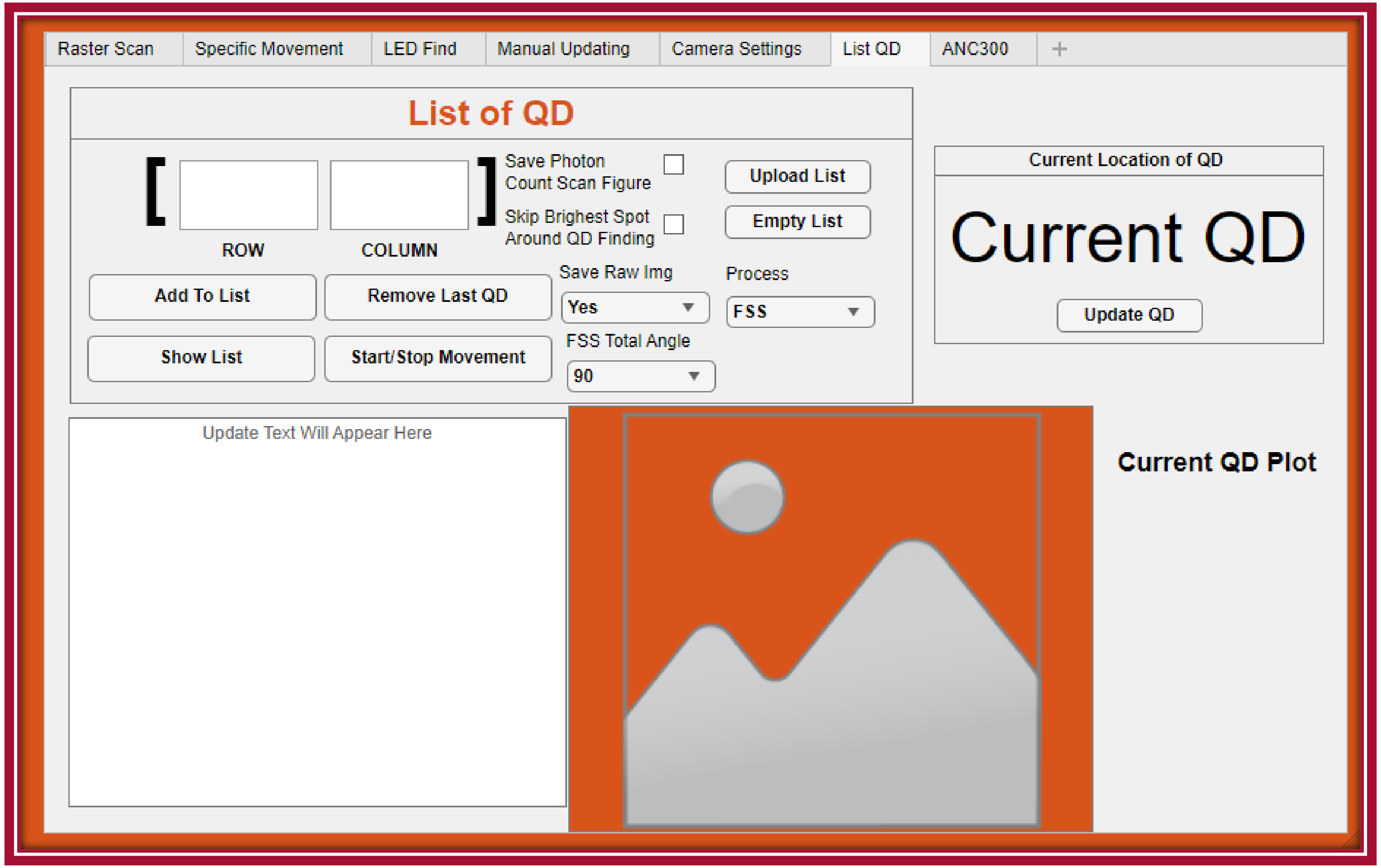
Camera Settings Tab

- Recommend to always have Start/Stop UI Camera pressed
  - Displays **live feed of nanowire positions**



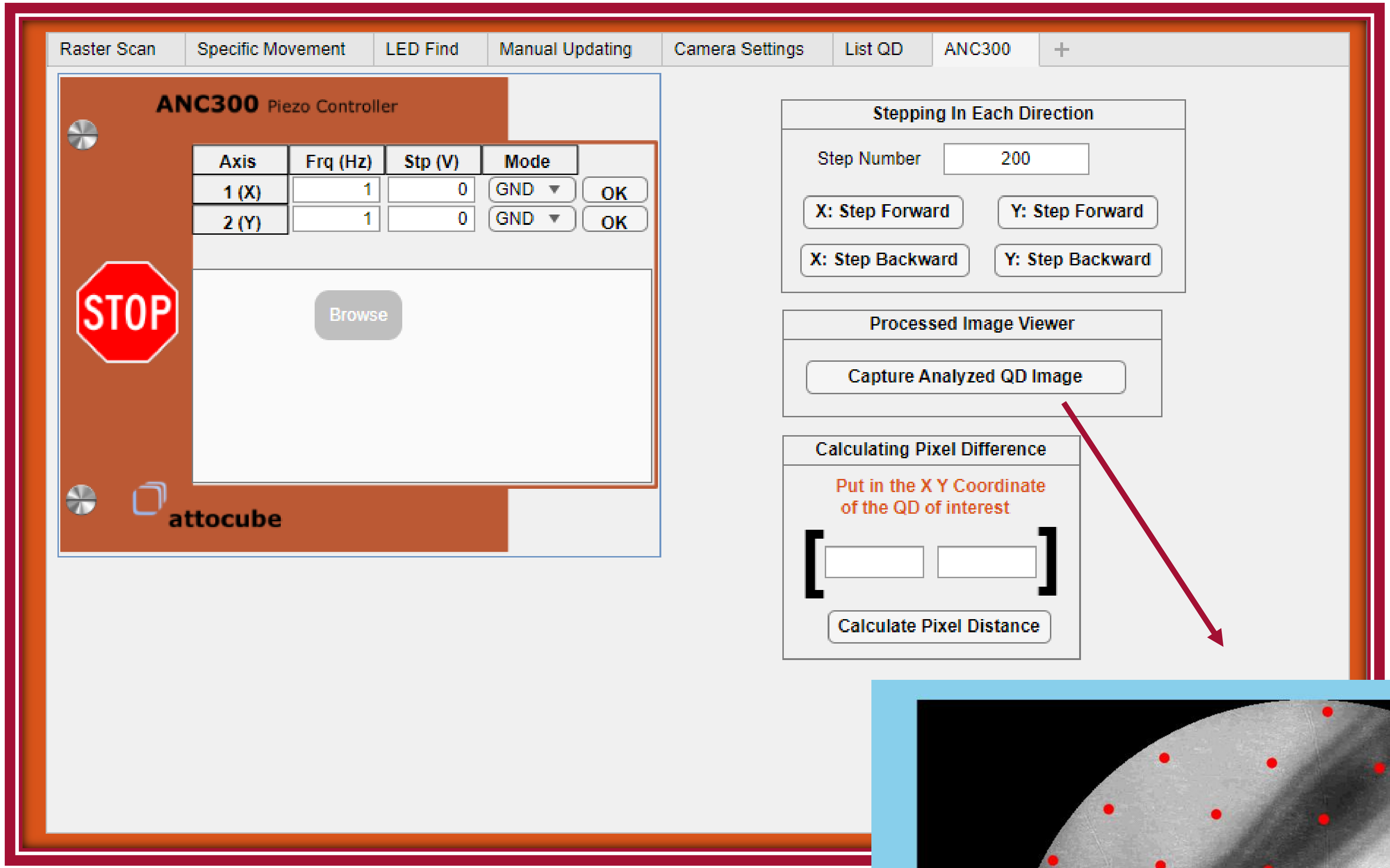
List QD Tab

- Allows user to get **FSS data** or **Emission Spectrums** on a list of QDs



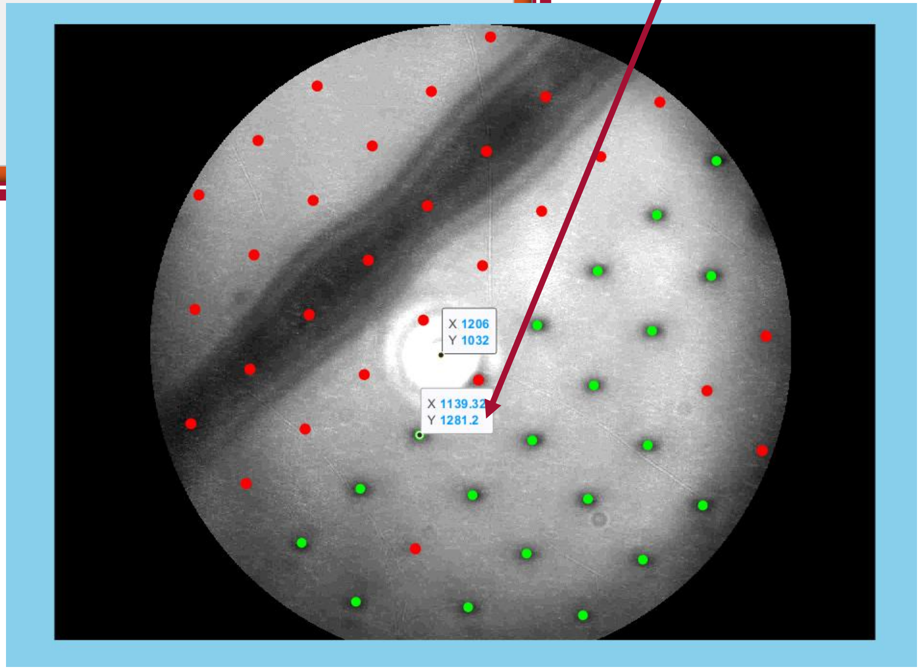
ANC300 Tab

- Crucial for calculating the accurate settings user must put into the **manual updating tab** after **Cryostat cycling**



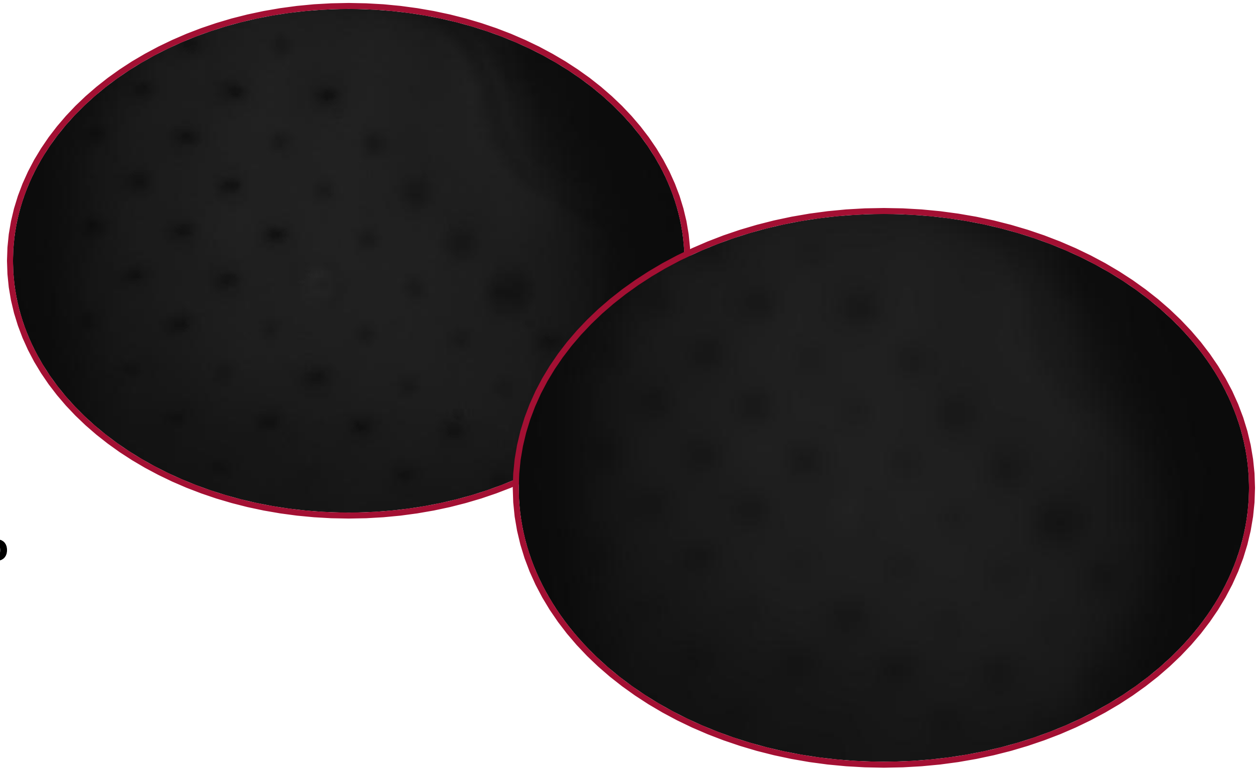
If this was dot user traveled from, put these coordinates in Calculation Panel

Example of an Analyzed QD Position Image



Small Tweaks to Code

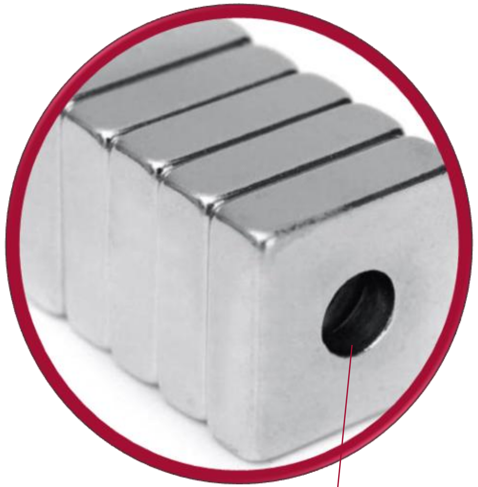
- **Issue:** attempt to snap a position photo before movement completed, **blurry image = undetectable dots**
- **Fix at the time:** introduced a manually defined extra pause via testing (**defined as 2.5 seconds)**
- **New Fix:** figured out how to translate byte data from piezo into voltage (0 = no movement etc.)
- Saved **time of 2 seconds per dot**
  - translated to **400 seconds saved per column or 7 minutes**
- **Safety Net:** If a movement takes longer than expected — for example, due to an unexpected **power loss or a stuck piezo stage** —algorithm **detects the issue and triggers an emergency stop**

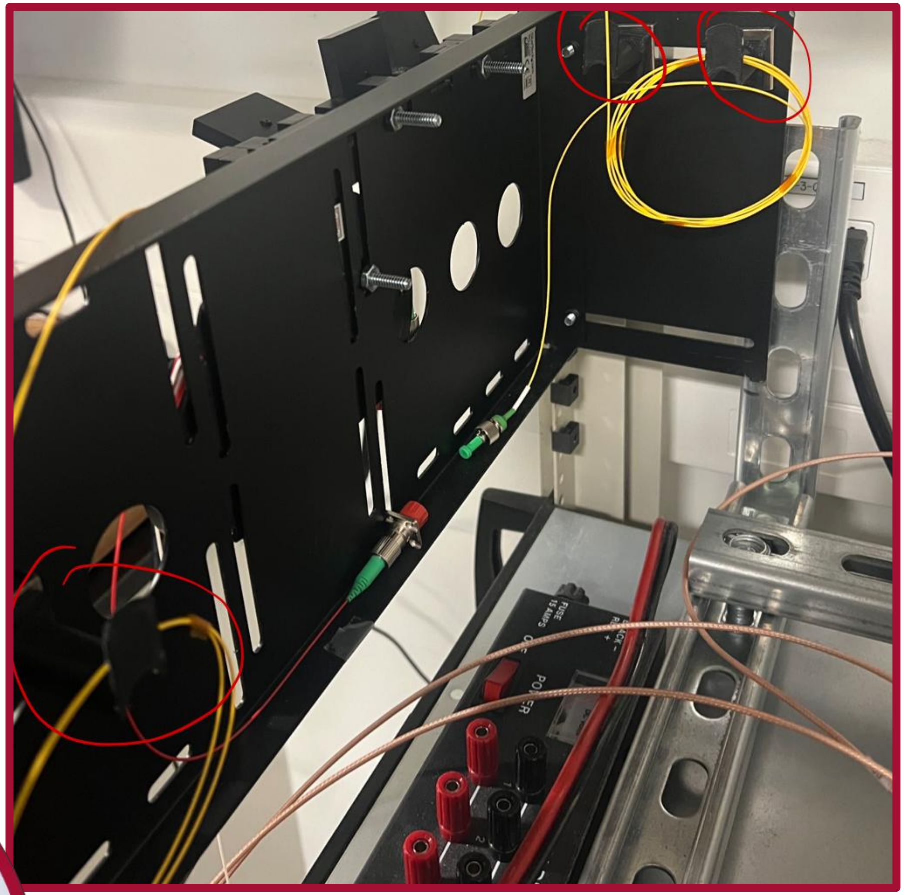


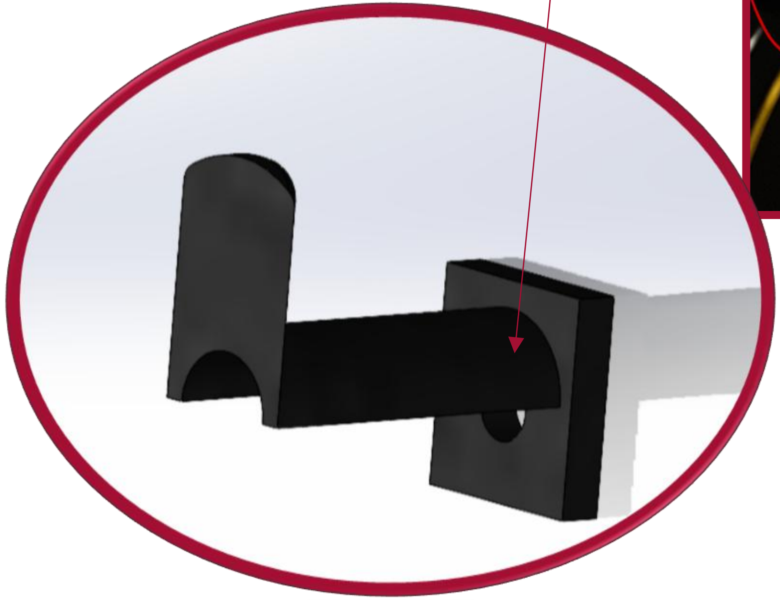
Side Projects

Fiber Optic Organization

- Designed a **handful** of **different Fiber optic** hooks (magnetic and non-magnetic), currently used around the lab

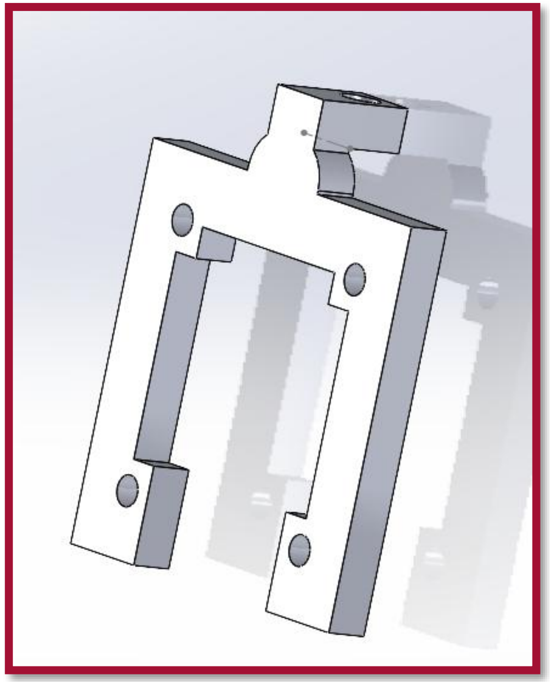


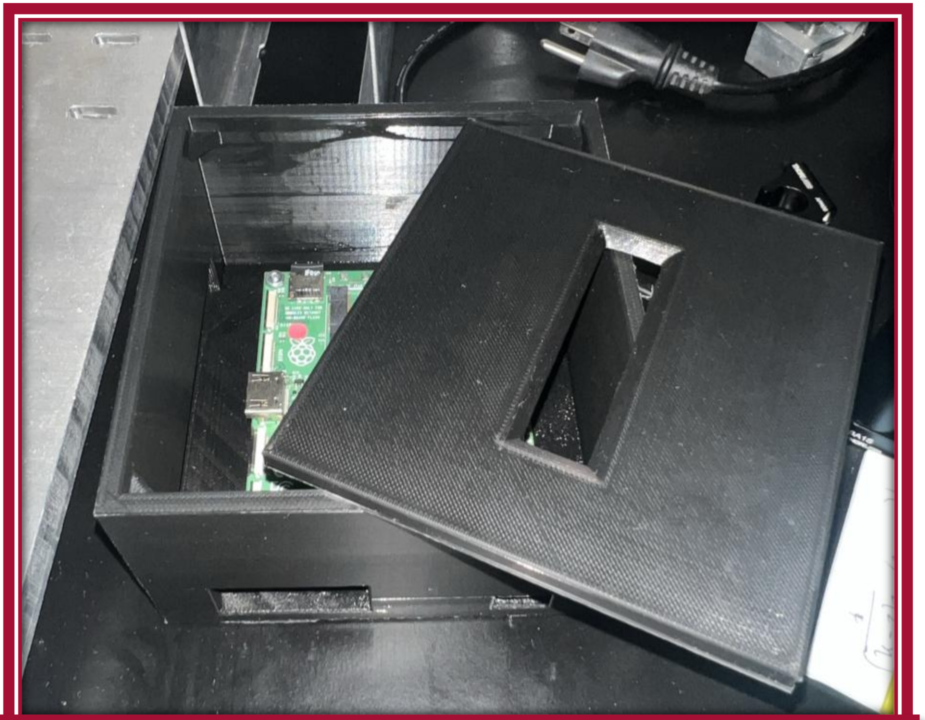


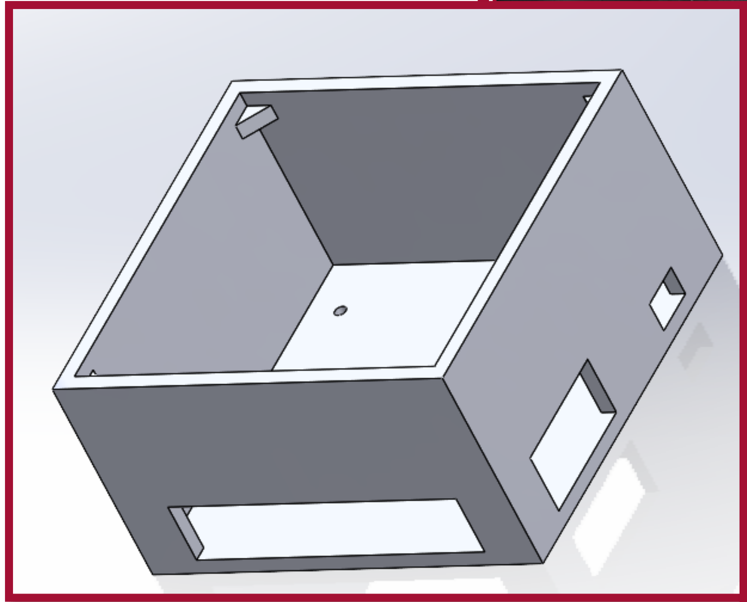


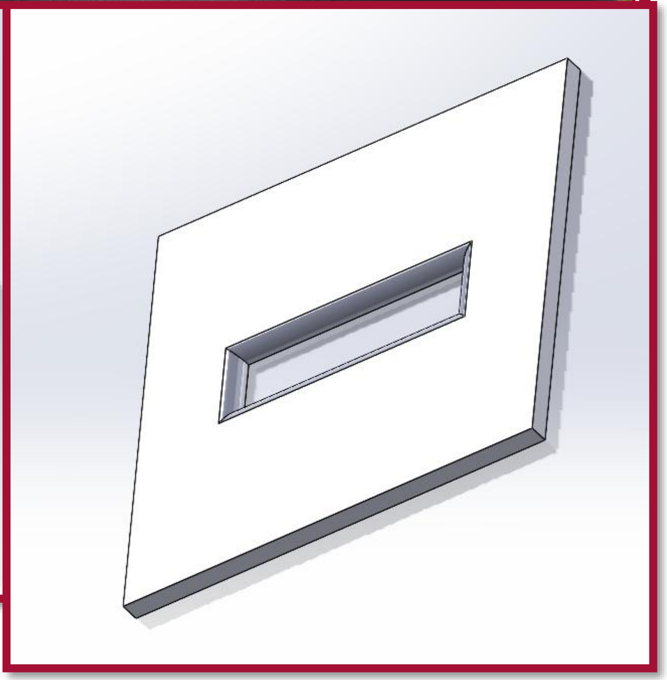
Raspberry Device Holders

- Designed a **simple box** with a **simple lid** for the Raspberry Pi Board that controls Cameras for cold atom setup
- Designed **new mounts** for **Raspberry Pi Cameras**









Raspberry Device Holders

- Designed a **simple box** with a **simple lid** for the Raspberry Pi Board that controls Cameras for cold atom setup
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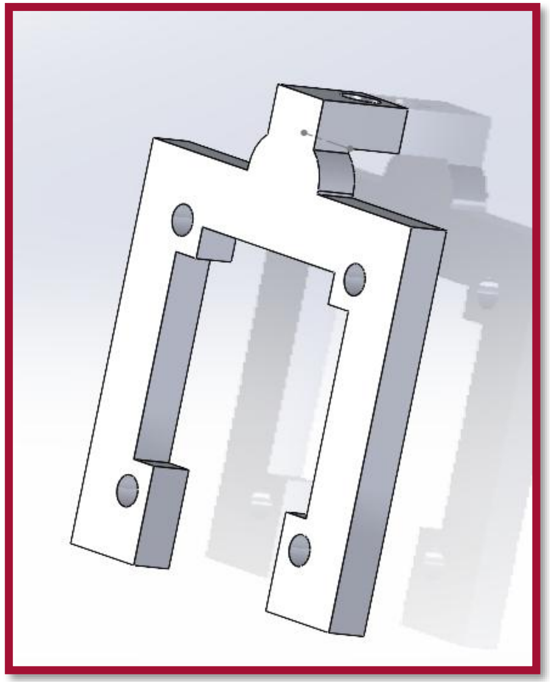
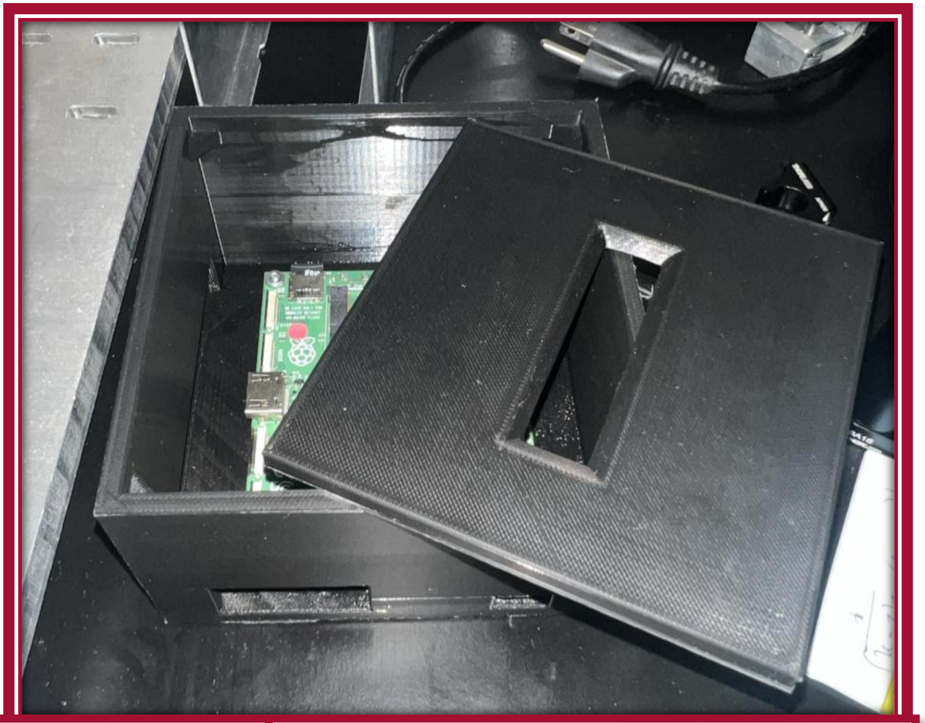
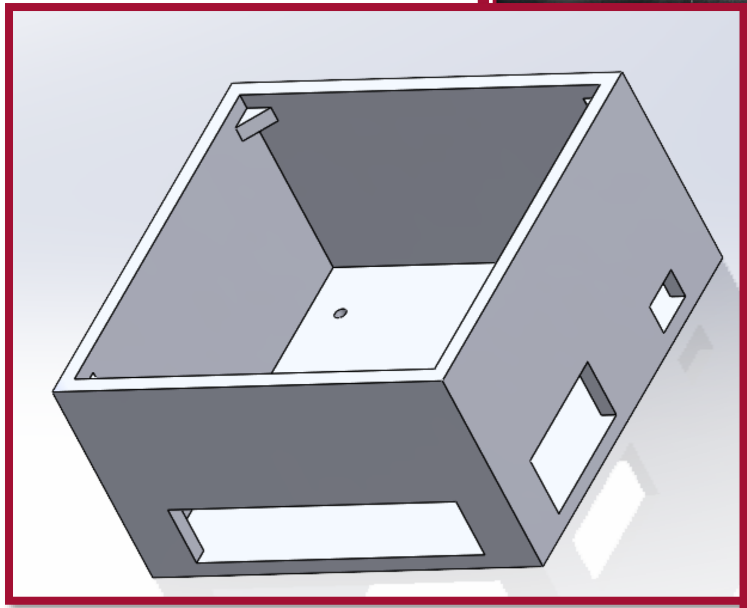
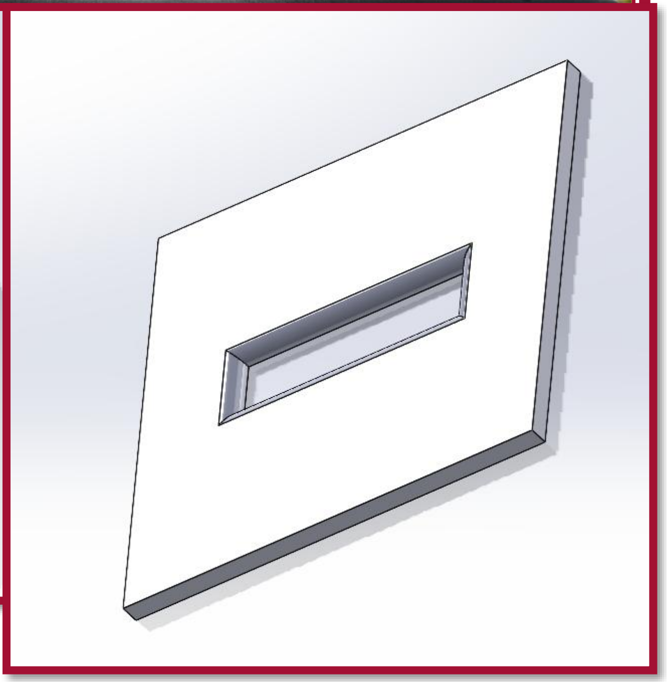




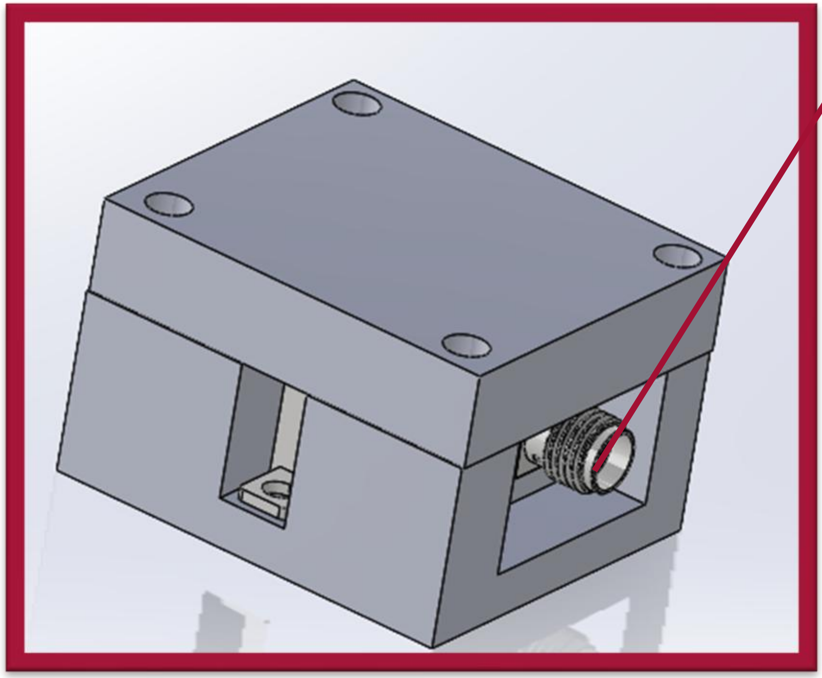




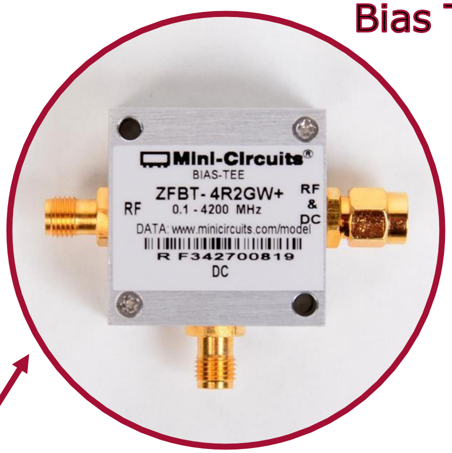
Custom New Cheap Photo Detector

- Currently working on designing a new custom high-speed fiber-optic detector
- Already have existing one, however **expensive and thus overkill for laser locking purposes**

Bias Tee Holder



Bias Tee



Fast Photo Diode Holder

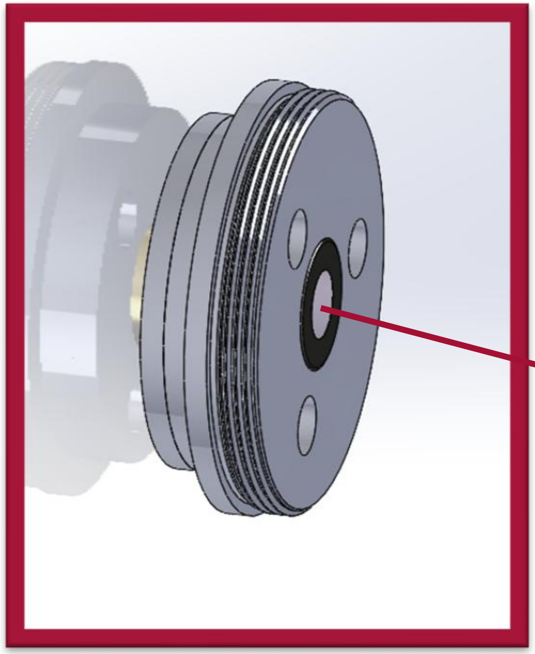
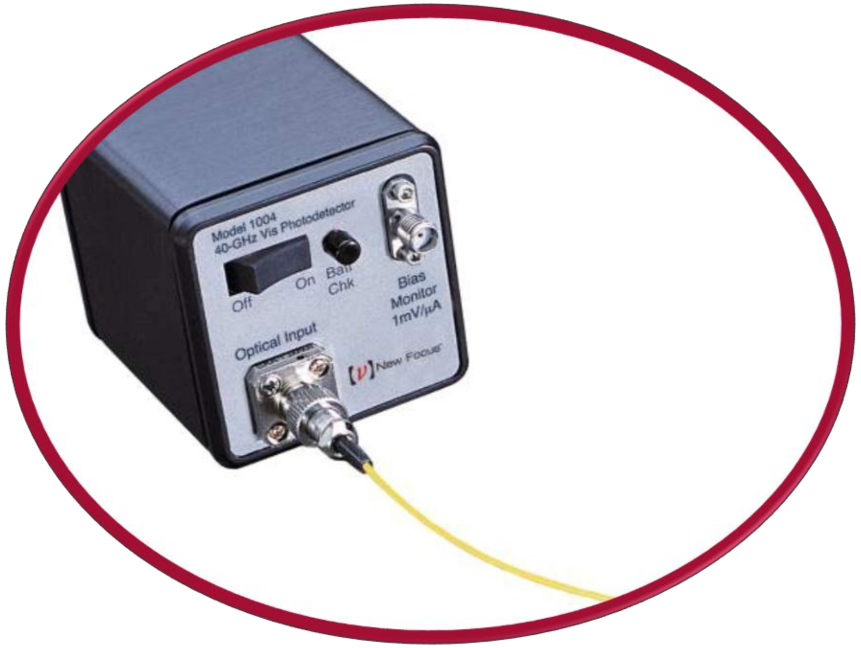
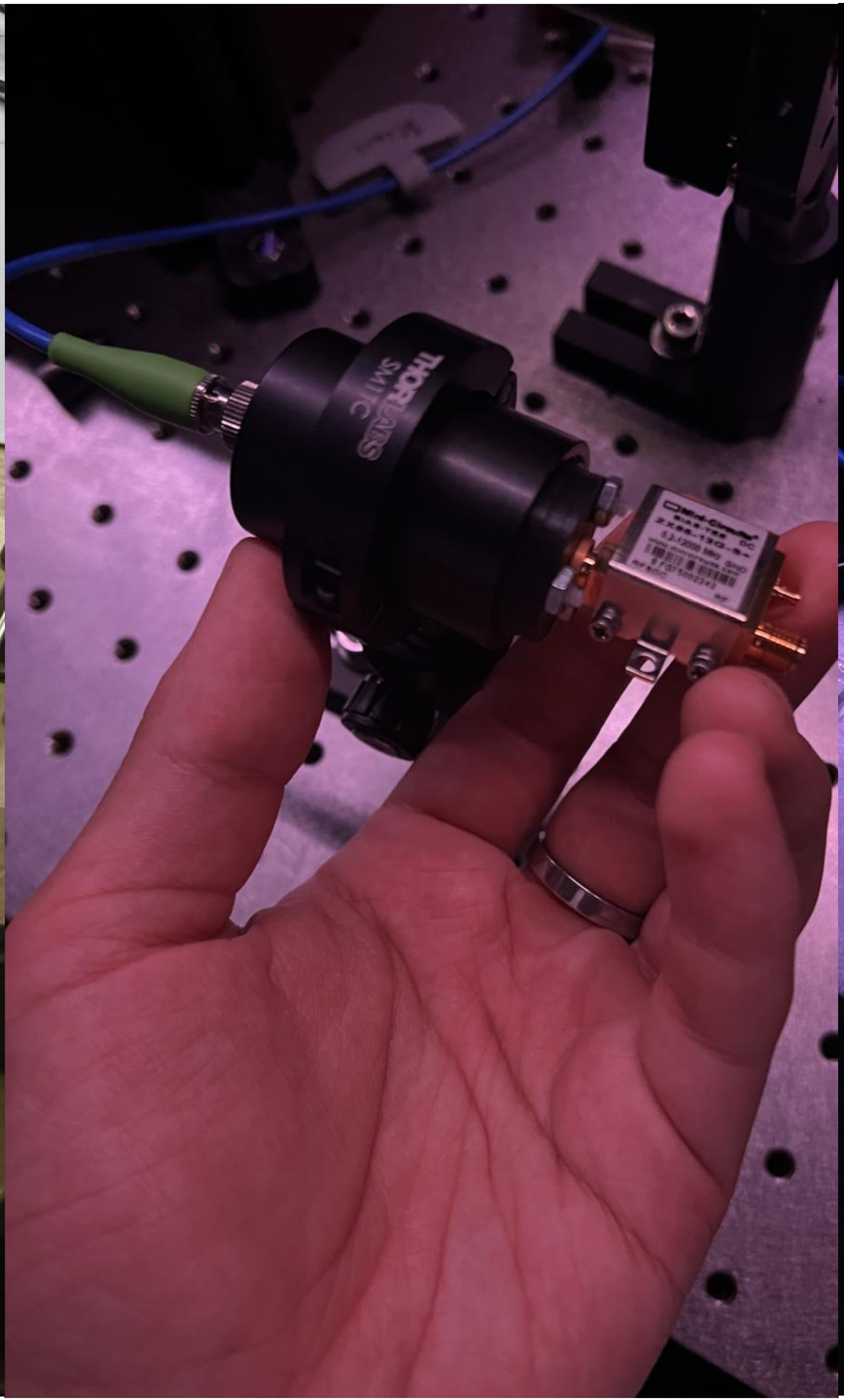
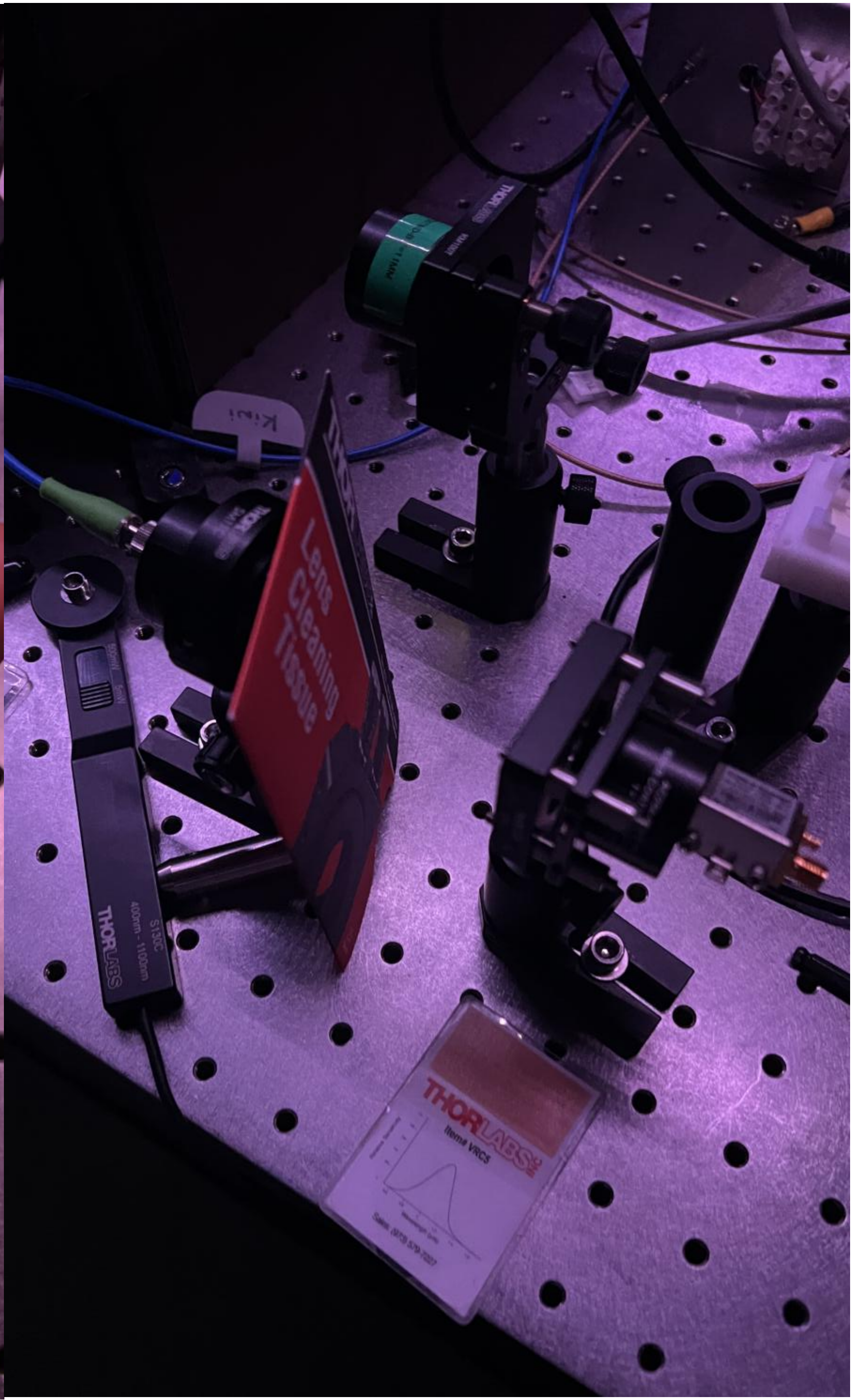


Photo Detector to Replace



Fast Photo Diode Holder


THORLABS
SM1TC


Lens Cleaning Tissue
THORLABS
S130C
400nm - 1100nm
THORLABS
Item# VRC5